CHAPTER 8 CUMULATIVE IMPACTS

8.1 Introduction

Under the CEQ NEPA implementing regulations, when preparing an EIS, NHTSA must consider the direct and indirect effects, as well as the cumulative impacts, of the Proposed Action and alternatives. CEQ defines direct effects as impacts "which are caused by the action and occur at the same time and place."[1] By contrast, indirect effects are impacts "which are caused by the action and are later in time or farther removed in distance, but are still reasonably foreseeable."[2] A cumulative impact is defined as "the impact on the environment which results from the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions regardless of what agency (federal or non-federal) or person undertakes such other actions. Cumulative impacts can result from individually minor but collectively significant actions taking place over a period of time."[3] The purpose of analyzing cumulative impacts is to ensure that federal decision-makers consider the full range of consequences of the Proposed Action and alternatives within the context of other actions, regardless of what agency or person undertakes them, over time.

Section 8.2, *Methods*, outlines NHTSA's approach to defining the scope for the cumulative impact analysis and identifying the relevant past, present, and reasonably foreseeable actions that contribute to cumulative impacts. The following sections focus on cumulative effects in key impact areas analyzed in the EIS: Section 8.3, *Energy*; Section 8.4, *Air Quality*; Section 8.5, *Other Impacts*; and Section 8.6, *Greenhouse Gas Emissions and Climate Change.*

8.2 Methods

This section describes NHTSA's approach to defining the temporal and geographic scope of the cumulative impact analysis and to identifying other past, present, and reasonably foreseeable future actions.

8.2.1 Temporal and Geographic Scope of Analysis

The timeframe for this analysis of cumulative impacts extends from 2020 through 2050 for energy, air quality, and other impacts, and through 2100 for greenhouse gas (GHG) and climate impacts. As noted in Chapter 5, *Greenhouse Gas Emissions and Climate Change*, the inherently long-term nature of the impacts of increasing GHG accumulations on global climate requires that GHG emissions for the Proposed Action and alternatives be estimated over a longer period than other environmental impacts. The geographic focus of this analysis for energy use and air quality impacts is national in scope while the analysis of climate impacts is global in scope, because GHG emissions in the United States may cause impacts around the world. This temporal and geographic focus is consistent with the analysis of direct and indirect impacts in Chapter 3, *Energy*, Chapter 4, *Air Quality*, Chapter 5, *Greenhouse Gas Emissions and Climate Change*, and Chapter 7, *Other Impacts*. This focus and the impact analysis are based on the

[1] 40 CFR § 1508.8(a) (2019).

[2] 40 CFR § 1508.8(b) (2019).

[3] 40 CFR § 1508.7 (2019).

reasonable ability of NHTSA to model or describe fuel consumption and emissions for the light-duty vehicle sector.

8.2.2 Identifying Past, Present, and Reasonably Foreseeable Future Actions

The cumulative impact analysis evaluates the impact of the Proposed Action and alternatives in combination with other past, present, and reasonably foreseeable future actions that affect the same resources. The range of actions considered includes other actions that have impacts that add to, or offset, the anticipated impacts of the proposed fuel economy standards on resources analyzed in this SEIS. The other actions that contribute to cumulative impacts can vary by resource and are defined independently for each resource. However, the underlying inputs, models, and assumptions of the CAFE Model (Section 2.3.1, *CAFE Model*) already take into account many past, present, and reasonably foreseeable future actions that affect U.S. transportation sector fuel use and U.S. mobile source air pollutant emissions. For example, the CAFE Model incorporates the 2021 Annual Energy Outlook (AEO), which includes assumptions and projections relating to fuel prices. The CAFE Model also uses "upstream" process emission factors generated by Argonne National Laboratory's Greenhouse Gases, Emissions, and Energy Use in Transportation (GREET) model, which incorporates U.S. air pollutant emissions regulations applicable to upstream processes, as well as tailpipe emission factors generated using the U.S. Environmental Protection Agency's (EPA) Motor Vehicle Emission Simulator (MOVES) model, which reflects U.S. regulations impacting vehicular emissions of criteria pollutants. Further, the baseline of analysis for measuring the climate impacts of the Proposed Action and alternatives is based on a global emissions scenario that includes assumptions about known policies and initiatives that affect global GHG emissions. Therefore, analysis of direct and indirect impacts of the Proposed Action and alternatives inherently (and appropriately) incorporates projections about the impacts of past, present, and reasonably foreseeable future actions to develop a realistic baseline. Because the universe of other reasonably foreseeable actions that would combine with the Proposed Action and alternatives on the relevant resource areas is limited, this chapter supplements the earlier chapters in analyzing the incremental impacts of the Proposed Action and alternatives when added to other past, present, and reasonably foreseeable future actions.

For energy, air quality, and other impacts, the other actions considered in their respective cumulative impact analyses are predictable actions where meaningful conclusions on impacts or trends relative to impacts of the Proposed Action and alternatives can be discerned. For these impact areas, the impacts described in Chapters 3, 4, and 7 are related to the widespread use of gasoline and diesel fuel to power light-duty vehicles. Some evidence, however, suggests that manufacturers may introduce a higher proportion of electric vehicles (EVs) into their fleets, which would affect the impacts reported in those chapters. This potential change in fuel source for light-duty vehicles is therefore a focus of the analysis in this chapter. In addition, NHTSA considers impacts related to new federal policies regarding energy production and use.

The cumulative impact analysis for GHG emissions and climate impacts is based on a global-scale emissions scenario because it is not possible to individually identify and define the incremental impact of each action during the analysis period (2021 through 2100) that could contribute to global GHG emissions and climate change. Instead, examples of some known actions that contribute to the underlying emissions scenario provide a national and an international perspective.

8.3 Energy

[Section forthcoming]

8.4 Air Quality

8.4.1 Scope of Analysis

The timeframe for the cumulative air quality impact analysis extends from 2020 through 2050. This analysis focuses on potential U.S. air quality impacts associated with changes in the U.S. light-duty vehicle fleet that could result from new federal energy policy and global market trends, but the geographic area of interest is U.S. emissions sources (upstream and downstream). This temporal and geographic focus is consistent with the analysis of direct and indirect air quality impacts in Chapter 4, *Air Quality*.

8.4.2 Analysis Methods

The methods NHTSA used to characterize the impacts of the Proposed Action and alternatives on emissions and air quality are described in Section 4.1.2, *Methods*. The methods and assumptions for the cumulative analysis are qualitative rather than quantitative because of uncertainties in future trends.

8.4.3 Other Past, Present, and Reasonably Foreseeable Future Actions

As discussed in Chapter 4, *Air Quality,* aggregate emissions associated with vehicles have decreased substantially since 1970, even as VMT has nearly doubled (Davis and Boundy 2021; EPA 2021a). The primary actions that have resulted in downstream emissions decreases from vehicles are the EPA Tier 1, Tier 2, and Tier 3 Motor Vehicle Emission and Fuel Standards. EPA has issued similar emissions standards for transportation sources other than motor vehicles, such as locomotives, marine vessels, and recreational vehicles, as well as standards for engines used in construction equipment, emergency generators, and other nonvehicle sources.

Upstream emissions associated with vehicles also have decreased (on a per-gallon fuel basis) since 1970 (EPA 2021a) as a result of continuing EPA and state regulation of stationary emissions sources associated with fuel feedstock extraction and refining, and with power generation (on a per-kilowatt hour basis). EPA regulations relevant to stationary source emissions include New Source Performance Standards, National Emissions Standards for Hazardous Air Pollutants, the Acid Rain Program under Title IV of the Clean Air Act, the Cross-States Air Pollution Rule, and the Mercury and Air Toxics Standards Rule. State air quality agencies have issued additional emissions control requirements applicable to stationary sources as part of their State Implementation Plans.

As discussed in Section 8.3, *Energy*, market-driven changes in the energy sector are expected to affect U.S. emissions and could result in future increases or decreases in emissions. Potential changes in federal regulation of energy production and emissions from industrial processes and power generation also could result in future increases or decreases in aggregate emissions from these sources.

8.4.4 Cumulative Impacts on Air Quality

Beyond reducing domestic gasoline consumption, the proposed standards affect energy supply and use by decreasing domestic petroleum production and refining while also increasing electricity generation for PHEVs and BEVs. Overall emissions of any specific criteria and toxic air pollutant could decrease in some years and increase in others, depending on the balance of changes in tailpipe and upstream emissions. As described in Chapter 3, *Energy*, in recent years, the electric utilities have been shifting away from coal toward natural gas and renewable energy due in part to the regulatory costs associated with coal plants, the cheap, abundant supply of natural gas, and decreasing costs of solar and wind energy development. To the degree to which fuel use in the light-duty transportation sector decreases, upstream energy use associated with feedstock extraction and refining, distribution, and storage could decrease proportionally, thereby decreasing emissions associated with that upstream energy use (although such decreases could be dampened by suppliers' participation in the global markets for petroleum and petroleum products). Upstream emissions associated with sources other than energy use also could decrease. For example, decreases in oil and gas development would decrease emissions from associated processes such as hydraulic fracturing. Changes in other federal rules that affect the oil and gas industry, such as the Bureau of Land Management's methane waste prevention regulations (43 CFR 3160 and 3170), would affect the size of these emissions changes.

Temporal patterns in charging of EVs by vehicle owners would affect any increase in power plant emissions. Electrical grid operators optimize costs and reliability by dispatching power capacity in different combinations depending on the varying demand for electricity. As a result, overall emission rates from the power plant fleet (i.e., electric grid mix) are different during hours of peak electrical demand, when peakload power plants are operating, and off-peak hours, when predominantly baseload power plants are operating. Charging EVs during these off-peak hours is generally advantageous in terms of grid reliability and electricity generation costs. The CAFE Model accounts for increased electricity generation to charge PHEVs and BEVs by scaling up the energy required in the rule's upstream emission inventories.

Trends in the prices of fossil fuels and the costs of renewable energy sources will affect the generation mix and, consequently, the upstream emissions from EVs. Continuation of the current relatively low prices for natural gas would encourage continued substitution of natural gas for other fossil fuels. Continued decreases in the costs of renewable energy would encourage substitution of renewable energy sources for fossil fuels. Continuation of either of these economic trends likely would lead to lower total emissions from EV charging. Conversely, a reversal of these trends would lead to higher total emissions from EV charging.

Annual Energy Outlook forecasts of power generation used in the CAFE Model account for existing legislation and other regulatory actions that affect power plant emissions. To the extent that these requirements may be amended in future years when the EV percentage of light-duty vehicle sales has increased, power sector emissions for EV charging would change accordingly.

Similarly, the forecasts of upstream and downstream emissions that underlie the impact analysis assume the continuation of current emissions standards (including previously promulgated future changes in standards) for vehicles, oil and gas development operations, and industrial processes such as fuel refining. These standards have become more stringent over time as state and federal agencies have sought to reduce emissions to help bring nonattainment areas into attainment. To the extent that the trend toward more stringent emissions standards could change in the future, total nationwide emissions from vehicles and industrial processes could change accordingly.

Cumulative changes in health impacts due to air pollution are expected to be consistent with trends in emissions and population exposure. Higher emissions in a geographic area would be expected to lead to an increase in overall health impacts in that area, while lower emissions would be expected to lead to a decrease in health impacts in that area, compared to conditions in the absence of cumulative impacts. Population distribution varies geographically, and as a result, a given amount of emissions would have greater health impacts in an area with greater population than in an area with less population. The level of population exposure in an area also is affected by the meteorological and topographical conditions in that area because these factors affect the dispersion and transport of emissions in the atmosphere. In addition, populations living or working near roadways could experience relatively greater exposure to tailpipe emissions, while populations living or working near upstream facilities (e.g., refineries) could experience relatively greater exposure to upstream emissions. An individual geographic area could experience either an increase or decrease in cumulative impacts under the proposed standards, depending on the relative magnitudes of effects from tailpipe versus upstream emissions that would affect that area.

8.5 Other Impacts

8.5.1 Scope of Analysis

Resource areas covered in the cumulative analysis are the same as those addressed in the direct and indirect impact analysis (Chapter 7, *Other Impacts*), including land use and development, hazardous materials and regulated wastes, historical and cultural resources, noise, and environmental justice. The timeframe for this analysis of other cumulative impacts extends from 2040 through 2050. This analysis considers potential impacts associated with global light-duty vehicle market trends, but the geographic area of interest is the United States. This temporal and geographic focus is consistent with the analysis of other direct and indirect impacts in Chapter 7.

8.5.2 Analysis Methods

The analysis methods for assessing cumulative impacts on the resource areas described in this section are consistent with the methods for determining direct and indirect impacts (Chapter 7, *Other Impacts*). However, the cumulative impact scenario considers the additional actions described in Section 8.5.3, *Other Past, Present, and Reasonably Foreseeable Future Actions*.

8.5.3 Other Past, Present, and Reasonably Foreseeable Future Actions

The analysis of other cumulative impacts builds upon the cumulative analysis for energy and air quality as described in Section 8.3.3, *Other Past, Present, and Reasonably Foreseeable Future Actions* (energy) and 8.4.3, *Other Past, Present, and Reasonably Foreseeable Future Actions* (air quality).

8.5.4 Cumulative Impacts on Other Resources

8.5.4.1 Land Use and Development

Section VII.A.4 and Section VI.D of the PRIA provide a discussion of VMT forecast. These sections detail that travel demand will recover rapidly from 2020's unprecedented decline, then increase through 2040 before declining gradually through 2050.Trends in electrification could be important insofar as the availability of convenient residential and workplace charging could both depend on and influence development.

Additionally, increases in fuel use resulting from reduced fuel costs or lower fleet-wide fuel economy could result in the need for additional oil extraction and refining, along with a potential need for new pipelines. Cumulative increases in EV use, however, may offset these increases in oil use, reducing the need for new capacity.

8.5.4.2 Hazardous Materials and Regulated Wastes

In terms of impacts on hazardous materials and regulated wastes, an increase in EV usage could decrease fuel production and combustion, offsetting the projected increases resulting from the Proposed Action and alternatives (Chapter 3, *Energy*). This would lead to an overall decrease in wastes generated from fuel extraction, production, and combustion, and a decrease in the number of hazardous material spills from extraction and refining. Reduced fuel costs per mile could result in consumer demand for less fuel-efficient vehicles or increased VMT, resulting in the opposite impacts. In addition, increased EV usage may result in an increase in wastes associated with the production and disposal of EV batteries. See Chapter 6, *Life-Cycle Implications of Vehicle Energy, Materials, and Technologies*, and Chapter 7, *Other Impacts*, for additional discussions of the waste impacts associated with EV usage.

8.5.4.3 Historic and Cultural Resources

As noted in Chapter 7, *Other Impacts* the main impact on historical and cultural resources associated with the Proposed Action and alternatives is the potential for increased acid rain and deposition. Acid rain and deposition corrodes metals and other building materials, reducing their historic and cultural value. Increases in EV usage have the potential to reduce fuel production and consumption impacts, thereby reducing pollutant emissions that cause acid rain and deposition and decreasing impacts on historical and cultural resources. Conversely, such emissions and impacts would increase if reduced fuel costs per mile result in increased consumer demand for less fuel-efficient vehicles or increased VMT.

8.5.4.4 Noise and Safety Impacts on Human Health

An increase in EV usage could reduce noise levels on roads and highways throughout the United States. However, as discussed in Chapter 7, *Other Impacts*, noise reductions from increased use of hybrid technologies could be offset at low speeds by manufacturer installation of pedestrian safety-alert sounds, as required by NHTSA (NHTSA 2016b). Conversely, increased driving associated with reduced fuel costs could result in higher noise levels on roads and highways throughout the United States.

8.5.4.5 Environmental Justice

Potential decreases in fuel production and consumption associated with increased EV usage are associated with the Proposed Action and alternatives. Direct land disturbance resulting from oil exploration and extraction is expected to decrease as well as decreases in air pollution produced by oil refineries. To the extent that minority and low-income populations live closer to oil extraction, distribution, and refining facilities or are more susceptible to their impacts (e.g., emissions, vibration, or noise) they are less likely to experience cumulative impacts resulting from these activities. With the revocation of EO 13783, *Promoting Energy Independence and Economic Growth,* decreased oil extraction and refining could be expected, as well as decreased vehicle operation due to increased fuel prices. Given these decreases, minority and low-income populations may experience fewer impacts resulting from these activities, but again, only to the extent that such populations are present near emissions sources. As noted in Chapter 7, a body of scientic literature signals disproportionate exposure of low-income and minority populations to poor air quality and proximity of minority and low-income populations to industrial, manufacturing, and hazardous waste facilities. Depending on communities' locations, energy sources, and other factors influencing distribution of air quality benefits, implementation of the Proposed Action and alternatives could could help to reduce disproportionate pollution impacts on overburdened communities and, as such, are not characterized as high and adverse.

Increased EV usage also has the potential to reduce criteria and toxic air pollutant impacts, while increased fuel supply and reduced fuel prices could have the opposite effect. Overall cumulative impacts on minority and low-income populations related to criteria and hazardous air pollutant emissions, including human health impacts, would likely be proportional to increases or decreases in such emissions and would not be characterized as high and adverse.

Lastly, there is evidence that minority and low-income populations may be disproportionately susceptible to the cumulative impacts of climate change (GCRP 2018a). Because minority and low-income populations may be disproportionately exposed to climate hazards (Ebi et al. 2018), depend on infrastructure that may be affected by climate change (Gowda et al. 2018), and have fewer resources to manage these impacts (Jacobs et al. 2018), these populations are disproportionately affected by climate change compared to the overall population. Although the action alternatives would reduce the potential increase in CO_2 concentrations and temperature under the cumulative impact analysis, the reductions would be a small fraction of the total increase in CO_2 concentrations and global mean surface temperature that is anticipated to occur. See Section 8.6.4, *Cumulative Impacts on Greenhouse Gas Emissions and Climate Change*, for a discussion of the cumulative impacts of the Proposed Action and alternatives. See Section 8.6.5, *Health, Societal, and Environmental Impacts of Climate Change*, for a thorough discussion of the cumulative impacts of climate change on minority, low-income, and other vulnerable populations.

8.6 Greenhouse Gas Emissions and Climate Change

Climate modeling conducted for this cumulative impacts analysis applies different assumptions about the effect of broader global GHG policies on emissions outside the U.S. passenger car and light truck fleets. The analysis of cumulative impacts also extends to include not only the immediate effects of GHG emissions on the climate system (atmospheric CO_2 concentrations, temperature, sea level, precipitation, and ocean pH) but also the impacts of past, present, and reasonably foreseeable future human activities that are changing the climate system on key resources (e.g., freshwater resources, terrestrial ecosystems, and coastal ecosystems).

8.6.1 Scope of Analysis

The timeframe for the cumulative GHG and climate change impact analysis extends from 2040 through 2100. This analysis considers potential cumulative GHG and climate change impacts associated with broader global GHG emissions policies in combination with the Proposed Action and alternatives. The geographic area of interest is domestic and global, as cumulative impacts of changes in GHG emissions occur on a domestic and global scale. This temporal and geographic focus is consistent with the analysis of direct and indirect GHG and climate change impacts in Chapter 5, *Greenhouse Gas Emissions and Climate Change*. A medium-high global emissions scenario that takes into account a moderate reduction in global GHG emissions was used in the climate modeling. This is consistent with global actions to reduce GHG emissions; specific actions that support the use of this scenario were included as examples.

8.6.2 Analysis Methods

The methods NHTSA used to characterize the impacts of the Proposed Action and alternatives on climate are described in Section 5.3, *Analysis Methods*. The methods and assumptions for the cumulative analysis are largely the same as those used in the direct and indirect impacts analysis, except 1) the global emissions scenario used for the main cumulative analysis is the Global Climate Change Assessment Model (GCAM) 6.0 scenario, and 2) multiple global emissions scenarios are modeled in the sensitivity analysis.

8.6.2.1 Global Emissions Scenarios Used for the Cumulative Impact Analysis

For the GHG and climate change analysis, cumulative impacts were determined primarily by using the GCAM 6.0 scenario as a reference case global emissions scenario that assumes a moderate level of global actions to address climate change. NHTSA chose the GCAM6.0 scenario as a plausible global emissions baseline because of the potential impacts of these reasonably foreseeable actions, yielding a moderate level of global GHG reductions from the GCAM Reference baseline scenario used in the direct and indirect analysis. For the cumulative analysis, the GCAM6.0 scenario serves as a reference scenario against which the climate impacts of the Proposed Action and alternatives can be measured. The GCAM6.0 scenario is the GCAM representation of a scenario that yields a radiative forcing of approximately 6.0 watts per square meter in the year 2100.

To evaluate the sensitivity of the results to a reasonable range of alternative emissions scenarios, NHTSA also used the Representative Concentration Pathways (RCP) 4.5 scenario and the GCAM Reference emissions scenario. The RCP4.5 scenario is a more aggressive stabilization scenario that illustrates the climate system response to stabilizing the anthropogenic components of radiative forcing at 4.5 watts per square meter in 2100.[4] The GCAM Reference scenario is the GCAM representation of a radiative forcing of 7.0 watts per square meter.

The GCAM6.0 scenario is the GCAM representation of the radiative forcing target (6.0 watts per square meter) of the RCP scenarios developed by the MiniCAM model of the Joint Global Change Research Institute. The GCAM6.0 scenario assumes a moderate level of global GHG reductions. It is based on a set of assumptions about drivers such as population, technology, socioeconomic changes, and global climate policies that correspond to stabilization, by 2100, of total radiative forcing and associated CO_2 concentrations at roughly 678 parts per million (ppm). More specifically, GCAM6.0 is a scenario that incorporates declines in overall energy use, including fossil fuel use, as compared to the reference case. In addition, GCAM6.0 includes increases in renewable energy and nuclear energy. The proportion of total energy use supplied by electricity also increases over time due to fuel switching in end-use sectors. CO_2 capture and storage plays an important role that allows for continued use of fossil fuels for electricity generation and cement manufacture, while limiting CO_2 emissions. Although GCAM6.0 does not explicitly include specific climate change mitigation policies, it does represent a plausible future pathway of global emissions in response to substantial global action to mitigate climate change. Consequently, NHSTA believes that GCAM6.0 represents a reasonable proxy for the past, present, and

[4] Radiative forcing is the net change in Earth's energy balance and is used in climate modeling to quantify the climate's response to change due to a perturbation. Small changes in radiative forcing can have large implications on surface temperature and sea ice cover. The radiative forcing from scenarios of future emissions projections are benchmarks used to understand the drivers of potential future climate changes and climate response scenarios (IPCC 2013b).

reasonably foreseeable GHG emissions through 2100, and is used for that purpose in this cumulative impact analysis on GHG emissions and climate change.

For the cumulative impact analysis, the difference in annual GHG emissions under the Proposed Action and alternatives compared to the No Action Alternative was calculated. This change was then applied to the GCAM6.0 scenario to generate modified global-scale emissions scenarios, which show the impact of the Proposed Action and alternatives on the global emissions path. For example, emissions from passenger cars and light trucks in the United States in 2040 under the No Action Alternative are estimated to be 1,215 million metric tons of carbon dioxide ($MMTCO_2$); emissions in 2040 under Alternative 3 are estimated to be 1,093 $MMTCO_2$. The difference of 123 $MMTCO_2$ represents the decrease in cumulative emissions projected to result from Alternative 3.[5] Cumulative global CO_2 emissions for the GCAM6.0 scenario in 2040 are estimated to be 49,034 $MMTCO_2$ and are assumed to incorporate the level of emissions from passenger cars and light trucks in the United States under the No Action Alternative. Cumulative global emissions under Alternative 3 are, therefore, estimated to be 123 $MMTCO_2$ less than this reference level or 48,911 $MMTCO_2$ in 2040 under the cumulative impacts analysis.

8.6.2.2 Sensitivity Analysis

The methods and assumptions for the sensitivity analysis are largely the same as those used in the direct and indirect impacts analysis, with the exception of the climate scenarios chosen. For the cumulative impacts analysis, the sensitivity analysis also assesses the sensitivity around different global emissions scenarios. NHTSA assumed multiple global emissions scenarios, including GCAM6.0 (687 ppm in 2100), RCP4.5 (544 ppm in 2100), and GCAM Reference scenario (789 ppm in 2100).

8.6.3 Other Past, Present, and Reasonably Foreseeable Future Actions

NHTSA chose the GCAM6.0 scenario as the primary global emissions scenario for evaluating climate impacts because regional, national, and international initiatives and programs now in the planning stages or already underway indicate that a moderate reduction in the growth rate of global GHG emissions is reasonably foreseeable in the future.

The following initiatives and programs are evidence of the past, present, or reasonably foreseeable actions that will affect GHG emissions. Global and domestic actions to reduce GHG emissions indicate that a moderate reduction in the growth rate of global GHG emissions is reasonably foreseeable in the future. NHTSA used this scenario to assess the impacts of the Proposed Action and alternatives when reasonably foreseeable increases in global GHG emissions are taken into account. Although it is not possible to quantify the precise GHG effects associated with these actions, policies, or programs when taken together (and NHTSA does not attempt to do so), collectively they illustrate an existing and continuing trend of U.S. and global awareness, emphasis, and efforts toward substantial GHG reductions. Therefore, a scenario that accounts for moderate reductions in the rate of global GHG emissions, such as the GCAM6.0 scenario, can be considered reasonably foreseeable under NEPA.

[5] The reduction in U.S. CO_2 emissions in 2040 under the Proposed Action and alternatives compared to the No Action Alternative ranges from 50 $MMTCO_2$ (Alternative 1) to 124 $MMTCO_2$ (Alternative 3).

8.6.3.1 United States: Regional and State Actions

The following actions in the United States are already underway or reasonably foreseeable.

- **Regional Greenhouse Gas Initiative (RGGI).** Launched on January 1, 2009, RGGI was the first mandatory, market-based effort in the United States to reduce GHG emissions (RGGI 2009). The initiative now includes the following 11 Northeast and Mid-Atlantic States: Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, Vermont, and Virginia.[6] Initially, RGGI states agreed to cap annual emissions from power plants in the region at 188 $MMTCO_2$ for 2009 through 2011, and 165 $MMTCO_2$ for 2012 through 2013 (RGGI 2014, Block 2014). In 2013, RGGI states lowered the regional emissions cap to 91 $MMTCO_2$ for 2014. The RGGI CO_2 cap then declined 2.5 percent per year from 2015 through 2020 (RGGI 2021). RGGI states plan reduce the overall cap by 30 percent between 2020 and 2030 (RGGI 2021). The proposed changes include an 11-state cap of 119.8 $MMTCO_2$ in 2021, which will decline to 86.9 $MMTCO_2$ in 2030 (RGGI 2021).
- **California 2016 Greenhouse Gas Reduction Legislation (Senate Bill 32).** In 2016, California passed Senate Bill 32, which codifies into law a GHG emissions reduction target of 40 percent below 1990 levels by 2030, equivalent to an absolute level of 260 $MMTCO_2e$ (California Air Resources Board [CARB] 2017). Initiatives to support this goal seek to reduce GHGs from cars, trucks, electricity production, fuels, and other sources. GHG-reduction measures under the California Air Resources Board's 2017 proposed scoping plan update include a continuation of the state's cap and trade program, a renewable portfolio standard, reduction of electric sector GHG emissions through the integrated resources plan process, low carbon fuel standards, zero emission and plug-in hybrid light-duty EV deployment, medium and heavy-duty vehicle GHG regulations, VMT reduction programs, the Short-Lived Climate Plan to reduce non-CO_2 GHGs, and refinery sector GHG regulations (CARB 2017).[7] Each of these measures is a known commitment or already underway or required. The cap-and-trade program took effect in 2013 for electric generation units and large industrial facilities and expanded in 2015 to include ground transportation and heating fuels (C2ES 2014). The known commitments are projected to reduce GHG emissions by 82 $MMTCO_2e$ by 2030 relative to a business-as-usual scenario (CARB 2017).
- **U.S. Climate Alliance.** Twenty-five U.S. governors have committed to reduce GHG emissions in their respective states consistent with the goals of the Paris Agreement. Alliance states have committed to implement policies that will reduce emissions at least 50 to 52 percent below 2005 levels by 2030 and achieve overall net-zero emissions as soon as practicable and before 2050 (U.S. Climate Alliance 2021). In 2005, emissions from these states totaled approximately 2.8 gigatons of CO_2 (Gt) (EIA 2018b, 2018c). From 2005 to 2018, Alliance states reduced emissions by 14 percent (U.S. Climate Alliance 2021). Based on policies in place in June 2018, Alliance states are projected to achieve

[6] New Jersey was a part of RGGI at its founding but dropped out of the program in May 2011. On January 29, 2018, New Jersey Governor Phil Murphy signed an executive order directing the state to rejoin RGGI, and the state officially rejoined in 2019. Virginia joined RGGI in July 2020. On October 3, 2019, Pennsylvania Governor Tom Wolf issued an executive order instructing the state's Department of Environmental Protection to join RGGI; however, as of April 2021, the state has not yet officially joined.

[7] In September 2019, NHTSA issued a final rule that established regulatory text explicitly preempting state and local laws relating to fuel economy standards established under the Energy Policy and Conservation Act (EPCA). As part of that action, EPA also withdrew the waiver it had previously provided to California for that State's GHG and ZEV programs under section 209 of the Clean Air Act. The Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule Part One: One National Program; Final Rule, 84 FR 51310 (Sept. 27, 2019).

combined emissions reductions of 18 to 25 percent below 2005 levels by 2025 (U.S. Climate Alliance 2019).

- **Zero Emission Vehicle (ZEV) Mandates.** In March 2012, California Governor Jerry Brown issued an EOestablishing several milestones on a path toward 1.5 million ZEVs in California by the year 2025 (California Office of the Governor 2013). Since 2013, California has created three ZEV action plans for obtaining this goal and introducing new goals; most recently with the goal of 5 million ZEVs by 2030 (California Governor's Office of Business and Economic Development 2021). In addition to these goals, California has issued several mandates with more details on California's ZEV plans of action. In 2015, the state updated the California Code of Regulations (CCR) at 13 CCR § 1962.2, which regulated the minimum ZEV credit percentage requirements for passenger cars, light-duty trucks, and medium-duty vehicles for MY 2018 and later. In 2018, this ZEV minimum percentage requirement was 4.5 percent, increasing to 22.5 percent for MY 2025 and beyond. In September 2020, California Governor Gavin Newsom established through EO (EO N-79-20), new targets for ZEVs including, 100 percent of in-state sales of new passenger vehicles and drayage trucks to be zero-emission by 2035, with medium- and heavy-duty vehicles to follow in 2045 (California Governor's Office of Business and Economic Development 2021). As of 2020, 13 states (the "Section 177" states[8]), making up more than one-third of total new car sales in the United States, have either adopted identical ZEV mandates to California's or ones with variations (Larson 2019).

- **CARB Framework Agreement.** In September 2019, the federal government revoked the federal Clean Air Act waiver for California that allows California to set more rigorous vehicle GHG emissions standards. Litigation is still ongoing for the official revocation of the waiver (CARB 2019a). In August 2020, California formalized bilateral agreements with six automakers to continue its emissions reduction framework developed in 2019 (CARB 2019b). These six automakers are BMW (of America), Ford, Honda, Volkswagen (of America), Audi, and Volvo. The framework agreement continues annual reductions of light-duty vehicle GHG emissions through MY 2026 under approximately the same rates as the standards set during the Obama administration (CARB 2020). The states that have previously adopted these California standards (the same 13 that adopted the ZEV mandates) have also supported California's GHG vehicle framework agreements.

8.6.3.2 United States: Federal Actions

The following federal actions are already underway or reasonably foreseeable:

- **Proposed Rule to Repeal the SAFE Vehicles Part One Final Rule.** On January 20, 2021, President Biden issued EO 13990, *Protecting Public Health and the Environment and Restoring Science To Tackle the Climate Crisis*,[9] which directed NHTSA to consider publishing for notice and comment by April 2021 a proposed rule suspending, revising, or rescinding the SAFE Vehicles Part One Final Rule, which declared that certain types of state regulation (in particular, California's ZEV mandates and regulation of vehicle GHG emissions) were preempted due to a perceived irreconcilable conflict with

[8] *Section 177 states* refers to the states that have adopted California's criteria pollutant and GHG emissions regulations under Section 177 of the Clean Air Act (42 U.S.C. § 7507).

[9] Executive Order 13990, Protecting Public Health and the Environment and Restoring Science To Tackle the Climate Crisis, 86 FR 7037 (Jan. 25, 2021).

NHTSA's fuel economy standards.[10] Pursuant to EO 13990, on April 22, 2021, NHTSA announced a proposed rule to repeal the SAFE Vehicles Part One Final Rule.[11] Relatedly, on April 28, 2021, EPA published a notice that it is reconsidering the 2019 EPA withdrawal of the waiver of preemption for California's ZEV mandate and GHG emissions standards.[12] If NHTSA finalizes its rule and EPA reinstates California's Clean Air Act waiver, then California and the Section 177 states will be permitted to move forward with their vehicle GHG regulations, in which case new passenger cars and light trucks sold in those states would have to meet these standards. The CAFE Model accounts for the GHG emissions reductions that would result from these state regulations, as described in Section X of the PRIA.

- **NHTSA and EPA Joint Rule on Fuel Economy and GHG Emissions Standards for Light-Duty Vehicles.** In August 2012, NHTSA and EPA issued joint final rules to further improve the fuel economy of and reduce CO_2 emissions for passenger cars and light trucks, as described in Chapter 1, *Purpose and Need for the Action*. The standards were projected to reduce average CO_2 emissions from new U.S. light-duty vehicles by 3.5 percent per year for MYs 2017–2021 (NHTSA and EPA 2011). Since the implementation of this joint rule, 10 of the 14 largest vehicle manufacturers selling cars in the U.S. market have made improvements to both fuel economy and CO_2 emissions. Between 2012 and 2019, the industry decreased CO_2 emissions by 21 gallons per mile and increased fuel economy by 1.3 mpg (EPA 2020p).
- **NHTSA and EPA Joint Phase 1 Rule on GHG Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Vehicles, MYs 2014–2018.** On September 15, 2011, NHTSA and EPA published the Phase 1 joint final rules to establish fuel efficiency and CO_2 standards for commercial medium- and heavy-duty on-highway vehicles and work trucks. The agencies' standards apply to highway vehicles and engines that are not regulated by the light-duty vehicle CAFE and CO_2 standards. NHTSA's Phase 1 mandatory standards for heavy-duty vehicles and engines began for MY 2016 vehicles, with voluntary standards for MYs 2014–2015. EPA's mandatory standards for heavy-duty vehicles began for MY 2014 vehicles. The combined standards were projected to reduce CO_2emissions by approximately 270 $MMTCO_2e$ over the lifetime of vehicles built during MYs 2014–2018 (NHTSA 2011).
- **NHTSA and EPA Joint Phase 2 Rule on GHG Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Vehicles, MYs 2018–2027.** In August 2016, NHTSA and EPA published the Phase 2 joint final rule to reduce fuel consumption and GHG emissions from heavy-duty vehicles. As with the Phase 1 standards, the Phase 2 fuel consumption and CO_2 standards apply to highway vehicles and engines that are not regulated by the light-duty vehicle CAFE and CO_2 standards. NHTSA and EPA Phase 2 standards apply to MYs 2018–2027 for certain trailers and to MYs 2021–2027 for heavy-duty vehicle engines, Classes 7 and 8 tractors (combination heavy-haul tractors), Classes 2 through 8 vocational vehicles (buses and work trucks), and Classes 2b and 3 heavy-duty pickups and vans (large pickup trucks and vans). The combined standards were projected to reduce GHG emissions by approximately 1,100 $MMTCO_2e$ over the lifetime of vehicles sold during MYs 2018–2027 (NHTSA 2016a).

[10] *The Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule Part One: One National Program; Withdrawal of Waiver; Final Rule*, 84 FR 51310 (Sept. 27, 2019).

[11] *Corporate Average Fuel Economy (CAFE) Preemption; Notice of Proposed Rulemaking*, 86 FR 25980 (May 12, 2021).

[12] *California State Motor Vehicle Pollution Control Standards; Advanced Clean Car Program; Reconsideration of a Previous Withdrawal of a Waiver of Preemption; Opportunity for Public Hearing and Public Comment*, 86 FR 22421 (Apr. 28, 2021).

- **Renewable Fuel Standard 2 (RFS2).** Section 211(o) of the Clean Air Act requires that a renewable fuel standard be determined annually that is applicable to refiners, importers, and certain blenders of gasoline and diesel fuel. Based on this standard, each obligated party determines the volume of renewable fuel that it must ensure is consumed as motor vehicle fuel. RFS2, which went into effect July 1, 2010, increases the volume of renewable fuel required to be consumed in the transportation sector from the baseline of 9 billion gallons in 2008 to 36 billion gallons by 2022, as written in 2010. Since 2014, the volumetric requirements have been modified to account for lower-than-expected growth in advanced and cellulosic biofuels (EPA 2015b).[13] The increased use of renewable fuels over 30 years, given a zero percent discount rate, is projected to reduce GHG emissions by 4,500 $MMTCO_2e$.
- **United States Appliance and Equipment Standards Program.** The National Appliance Energy Conservation Act of 1987 established minimum efficiency standards for many household appliances and has been authorized by Congress through several statutes. Since its inception, the program has implemented additional standards for more than 50 products, which represent about 90 percent of home energy use, 60 percent of commercial building use, and 29 percent of industrial energy use (DOE 2014). The program has avoided more than 3,000 $MMTCO_2$, and is expected to reduce GHG emissions by 7,900 $MMTCO_2e$ annually by 2030 (DOE 2016b).
- **Final rule to redefine terms under Department of Energy (DOE) lighting efficiency standards.** In 2007, the EISA directed DOE to conduct a rulemaking on efficiency standards for general service lamps (GSLs) and other incandescent lamps. In January 2017, DOE issued a final rule that revised and expanded the definition for GSL to include a broader range of incandescent lightbulbs, including those used for decorative and less-common purposes than general lighting (EPA 2017e). In February 2019, DOE issued a notice of proposed rulemaking to rescind the 2017 amendments, arguing that the definition revisions were not lawful according to the 2007 rulemaking directive (EPA 2019d). The rule to rescind the amendments was finalized in September 2019. The energy savings potential of the 2017 standards was estimated to be 27 quadrillion BTUs for lamps shipped between 2020 and 2049 (Kantner et al. 2017). The proposal had the potential to reduce GHG emissions by 540 $MMTCO_2e$ by 2030 (Kantner et al. 2017). In May 2021, DOE announced that it is re-evaluating its prior determination from 2019 statutory backstop requirement for GSLs, possibly reinstating the 2017 revision.
- **Revisions to the Methane New Source Performance Standards Rule.** In 2016, the New Source Performance Standards (NSPS) rule that targets controlling CH_4 leaks from oil and gas operations on public lands was finalized. In 2020, EPA issued two final rules that amended the 2016 NSPS. The first, published on September 14, 2020, finalized policy amendments to remove oil and gas transmission and storage operations and associated CH_4 emission limits under the oil and natural gas sector NSPS ("policy amendments final rule").[14] The second, published on September 15, 2020, finalized technical amendments that lowered leak mitigation requirements for compressor stations in the oil and gas industry and eliminated leak mitigation requirements for the industry's low-production wells, among other changes ("technical amendments final rule").[15] In June 2021, Congress passed a

[13] https://www.epa.gov/renewable-fuel-standard-program/final-renewable-fuel-standards-2014-2015-and-2016-and-biomass-based.

[14] *Oil and Natural Gas Sector: Emission Standards for New, Reconstructed, and Modified Sources Review; Final Rule*, 85 FR 57018 (Sept. 14, 2020).

[15] *Oil and Natural Gas Sector: Emission Standards for New, Reconstructed, and Modified Source Reconsideration; Final Rule*, 85 FR 57398 (Sept. 15, 2020).

joint resolution to disapprove (repeal) the policy amendments final rule (S.J.Res.14, 2021). In accordance with the Biden administration's direction in EO 13990, the EPA intends to reconsider the technical amendments final rule.[16] If the technical amendments final rule remains in place, CH_4 emissions can be expected to increase by 10 $MMTCO_2e$ by 2030.[17]

- **Proposal to Revise the Regulations on Ozone-Depleting Substance (ODS) Substitute Refrigerants Extension.** In 2016, EPA finalized a rule that updated the Clean Air Act Section 608 rule regulating ODS emissions reductions during appliance maintenance and leak repairs to also include substitute refrigerants such as hydrofluorocarbons (HFCs), specifically, the appliance maintenance and leak repair provisions. The rule also listed provisions to lower the threshold for which leaks to repair and required periodic leak inspections for equipment leaking above the threshold, repair verification tests, and record the disposal of appliances containing more than 5 and less than 50 pounds of refrigerants (EPA 2016d). In August 2017, EPA announced that it would revisit the 2016 rule's extension to include more refrigerants (HFCs), specifically, the appliance maintenance and leak repair provisions. In October 2018, a proposed rule was issued to withdraw the extension and additional provisions, arguing whether the agency held the statutory authority to extend the regulations initially (EPA 2018e). On December 27, 2020, the American Innovation and Manufacturing Act was enacted by Congress. The Act directs EPA to address the environmental impact of HFCs by: phasing down production and consumption, maximizing reclamation and minimizing releases from equipment, and facilitating the transition to next-generation technologies through sector-based restrictions. This action is expected to reduce GHG emissions by 4,700 $MMTCO_2$ from 2022 to 2050 (EPA 2021i).
- **United States and the Paris Agreement.** On April 22, 2021, President Biden submitted a Nationally Determined Contribution to the United Nations Framework Convention on Climate Change (UNFCCC) secretariat, with a target for the United States to achieve a 50 to 52 percent reduction in economy-wide net GHG pollution from 2005 levels by 2030. This target was submitted under the Paris Agreement, which entered into force on November 4, 2016. The United States formally withdrew from the Paris Agreement in November 2020, but then officially rejoined in February 2021. The Paris Agreement's goal is to limit global average temperature increase to well below 2°C (3.6°F) above preindustrial levels and pursue efforts to limit the increase to 1.5°C (2.7°F).

8.6.3.3 International Actions

The following international actions are already underway or reasonably foreseeable:

- **UNFCCC and the annual Conference of the Parties.** This international treaty was signed by many countries around the world (including the United States); it entered into force on March 21, 1994 and sets an overall framework for intergovernmental efforts to tackle the challenge posed by climate change (UNFCCC 2002).

  Kyoto Protocol. The Kyoto Protocol is an international agreement linked to the UNFCCC. The major feature of the Kyoto Protocol is its binding targets for 37 industrialized countries and the European Community for reducing GHG emissions, which covers more than half of the world's GHG emissions. These reductions amount to approximately 5 percent of 1990 emissions over the 5-year period 2008

[16] Spring 2021 Unified Agenda of Regulatory and Deregulatory Actions, RIN 2060-AV16. Available at: [HYPERLINK "https://www.reginfo.gov/public/do/eAgendaMain"] (last accessed June 22, 2021).

[17] *Oil and Natural Gas Sector: Emission Standards for New, Reconstructed, and Modified Source Reconsideration; Final Rule*, 85 FR 57398, 57434 (Sept. 15, 2020).

through 2012 (UNFCCC 2014a). The December 2011 COP-17 held in Durban, South Africa, resulted in an agreement to extend the imminently expiring Kyoto Protocol. The Second Commitment Period took effect on January 1, 2013, ran through December 2020, and required parties to reduce emissions by at least 18 percent below 1990 levels by 2020, a metric that was on pace to be exceeded, although data is not yet available (UNFCCC 2020). The parties in the second commitment period differ from those in the first (UNFCCC 2014a).

Additional Decisions and Actions. At COP-16, held in Cancun, Mexico in December 2010, a draft accord pledged to limit global temperature increase to less than 2°C (3.6 degrees Fahrenheit [°F]) above preindustrial global average temperature. At COP-17, the Parties established the Working Group on the Durban Platform for Enhanced Action to develop a protocol for mitigating emissions from rapidly developing countries no later than 2015, and to take effect in 2020 (UNFCCC 2014b). As of April 12, 2012, 141 countries had agreed to the Copenhagen Accord, accounting for the vast majority of global emissions (UNFCCC 2010). However, the pledges are not legally binding, and much remains to be negotiated. At COP-18, held in Doha, Qatar in November 2012, the parties also made a long-term commitment to mobilize $100 billion per year to the Green Climate Fund by 2020, which will operate under the oversight of the Conference of the Parties to support climate change-related projects around the world (UNFCCC 2012). At COP-19, held in Warsaw, Poland in November 2013, key decisions were made towards the development of a universal 2015 agreement in which all nations would bind together to reduce emissions rapidly, build adaptation capacity, and stimulate faster and broader action (UNFCCC 2014b). COP-19 also marked the opening of the Green Climate Fund, which began its initial resource mobilization process in 2014 (UNFCCC 2014c). At COP-20, held in Lima, Peru in December 2014, countries agreed to submit Intended Nationally Determined Contributions (country-specific GHG mitigation targets) by the end of the first quarter of 2015. COP-20 also increased transparency of GHG reduction programs in developing countries through a Multilateral Assessment process, elicited increased pledges to the Green Climate Fund, made National Adaptation Plans more accessible on the UNFCCC website, and called on governments to increase educational initiatives around climate change (UNFCCC 2014d). At COP-21, the Paris Agreement was adopted, which emphasizes the need to limit global average temperature increase to well below 2°C above preindustrial levels and pursue efforts to limit the increase to 1.5°C. The agreement urges countries to commit to a GHG reduction target by 2020 and to submit a new reduction target that demonstrates progress every 5 years thereafter. The United Nations will analyze progress on global commitments in 2023 and every 5 years thereafter. As of May 2021, 191 countries, including the United States, comprising over 97 percent of global GHG emissions had ratified, accepted, or approved the Paris Agreement (WRI 2021; UNFCCC 2021). Initial GHG emissions reduction targets announced by country signatories to the Paris Agreement are expected to result in global emissions that are 3.6 gigatons lower in 2030 than projected from pre-Paris national pledges (UNFCCC 2015). Based on country pledges from the Paris Agreement, global GHG emissions in 2030 are expected to be lower than those under the highest emissions scenario (RCP8.5) but higher than those under RCP4.5 and RCP6.0 (UNFCCC 2015). While the commitments to reduce GHG emissions cannot be extrapolated into a trend (i.e., there is significant uncertainty surrounding emissions before and after 2030), they demonstrate global action to reduce the historical rate of GHG emissions growth.

- **The European Union GHG Emissions Trading System.** In January 2005, the European Union Emissions Trading System commenced operation as the largest multi-country, multi-sector GHG emissions trading system worldwide (European Union 2018). The aim of the system is to help European Union member states achieve compliance with their commitments under the Kyoto Protocol (European Union 2015). This trading system does not entail new environmental targets;

instead, it allows for less expensive compliance with existing targets under the Kyoto Protocol. The scheme is based on Directive 2003/87/EC, which entered into force on October 25, 2003 (European Union 2015) and covers about 10,000 energy-intensive installations across the European Union. This represents 40 percent of Europe's emissions of CO_2 (European Union 2018). These installations include commercial aviation, combustion plants, oil refineries, and iron and steel plants, and factories making cement, glass, lime, brick, ceramics, pulp, and paper (European Union 2018). To achieve climate neutrality in the EU by 2050, the EU Emissions Trading System is under review with the aim to both expand the scope of coverage, but also update its target by reducing GHGs to at least 55 percent below 1990 levels by 2030 (European Union 2020). Installations covered by the Emissions Trading System reduced emissions by about 35 percent between 2005 and 2019 (European Union n.d.).

- **Fuel Economy Standards in Asia.** Both Japan and China have taken actions to reduce fuel use, CO_2 emissions, and criteria pollutant emissions from vehicles. Japan has invested heavily in research and development programs to advance fuel-saving technologies, has implemented fiscal incentives such as high fuel taxes and differential vehicle fees, and has mandated fuel economy standards based on vehicle weight class (using country-specific testing procedures [Japan 1015/JC08]). In 2015, Japan's Ministry of Land, Infrastructure, Transport, and Tourism finalized new fuel economy standards for light and medium commercial vehicles sold in 2022 that are a 23 percent increase from the 2015 prevailing standard (ICCT 2015). Similarly, China has implemented fuel economy standards, based on the Worldwide harmonized Light-duty Test Cycle instead of the previously used New European Driving Cycle. In December 2019, China set new standards for passenger vehicles produced or imported to an average target of 59 mpg.
- **China EV Targets.** China has established a program that effectively sets quotas for PEVs and fuel cell electric vehicles (FCVs), under which PEVs and FCVs were expected to make up at least 10 percent of each automaker's sales in China in 2019, and 12 percent in 2020 (ICCT 2021). Subsequent targets under Phase 2 of this policy will require these vehicles to make up 18 percent of total sales by 2023. China has not yet set a timetable to reach 100 percent EV sales but is expected to join other nations in phasing out sales of ICE vehicles by 2040.

- **Other International GHG mitigation efforts.** There are many nations adopting other national actions, such as cap-and-trade programs, to reduce GHG vehicle emissions. Some efforts from large emitters include:

  - In January 2021, China launched its new national emissions trading scheme, which allows market emitters to buy, sell, and/or trade emissions credits (ICAP 2021). These new plans build upon existing cap-and-trade efforts launched in December 2017. The updates include goals of a reduction in carbon emissions per unit of gross domestic product by 18 percent compared to the 2020 levels within the next 5 years, a peak of emissions before 2030, and carbon neutrality by 2060 (ICAP 2021).
  - Officially launched in 2017, India currently has a similar cap-and-trade program, which has been cited as the first program to include particulate matter (PM) aerosols within its emissions trading scheme program (University of Chicago 2019). As of 2019, India has also pledged to reduce emissions intensity by 33 to 35 percent compared to 2005 levels (Timperley 2019).
  - To date, many other countries have adopted a national cap-and-trade program including, but not limited to Mexico, Australia, Colombia, Chile, New Zealand, South Korea, Japan, and nearly all the nations within the European Union (Plumber and Popovich 2019).

8.6.4 Cumulative Impacts on Greenhouse Gas Emissions and Climate Change

8.6.4.1 Greenhouse Gas Emissions

NHTSA estimated the emissions resulting from the Proposed Action and alternatives using the methods described in Section 5.3, *Analysis Methods*.

8.6.4.2 Cumulative Impacts on Climate Change Indicators

Using the methods described in Chapter 2, *Proposed Action and Alternatives and Analysis Methods*, and Section 8.6.2, *Analysis Methods*, this section describes the cumulative impacts of the alternatives on climate change in terms of atmospheric CO_2 concentrations, temperature, precipitation, sea-level rise, and ocean pH. The impacts of this rulemaking, in combination with other reasonably foreseeable future actions, on global mean surface temperature, precipitation, sea-level rise, and ocean pH are relatively small in the context of the expected changes associated with the emissions trajectories in the GCAM scenarios. Although relatively small, primarily due to the global and multi-sectoral nature of climate change, the impacts occur on a global scale and are long-lasting.

The Model for the Assessment of Greenhouse-Gas Induced Climate Change (MAGICC) 6 scenario is a reduced-complexity climate model and well calibrated to the mean of the multi-model ensemble results for four of the most commonly used emissions scenarios (i.e., RCP2.6 [low], RCP4.5 [medium], RCP6.0 [medium-high], and RCP8.5 [high]) from the IPCC RCP series.

The GCAM6.0 scenario (Section 8.6.2.1, *Global Emissions Scenarios Used for the Cumulative Impact Analysis*) was used to represent the No Action Alternative in the MAGICC runs for the cumulative impacts analysis. Table 8.6.4-1 and Figure 8.6.4-1 through Figure 8.6.4-4 show the mid-range results of MAGICC model simulations for all alternatives for CO_2 concentrations and increase in global mean surface temperature in 2040, 2060, and 2100. As Figure 8.6.4-1 and Figure 8.6.4-3 show, the action alternatives would reduce the projected increase in CO_2 concentrations and temperature, but the reductions would be a small fraction of the total increase in CO_2 concentrations and global mean surface temperature. As shown in Table 8.6.4-1, Figure 8.6.4-1, and Figure 8.6.4-2, the band of estimated CO_2 concentrations as of 2100 is narrow, ranging from 687.29 ppm under the No Action Alternative to 686.55 ppm under Alternative 3. For 2040 and 2060, the corresponding ranges are similar. Because CO_2 concentrations are the key driver of all other climate effects, the small changes in CO_2 leads to small differences in climate effects. Compared with projected total global CO_2 emissions of 4,044,005 $MMTCO_2$ from all sources from 2021 to 2100 under GCAM6.0, the incremental impact of this rulemaking is expected to reduce global CO_2 emissions between 0.10 (Alternative 1) and 0.21 (Alternative 3) percent by 2100.

Table [STYLEREF 3 \s]-[SEQ Table * ARABIC \s 3]. Carbon Dioxide Concentrations, Global Mean Surface Temperature Increase, and Sea-Level Rise, and Ocean pH by Alternative[a]

	CO_2 Concentration (ppm)			Global Mean Surface Temperature Increase (°C)[b]			Sea-Level Rise (cm)[b]			Ocean pH[c]		
Alternative	2040	2060	2100	2040	2060	2100	2040	2060	2100	2040	2060	2100
Alt. 0 (No Action)	472.56	546.00	687.29	1.216	1.810	2.838	22.16	35.15	70.22	8.4150	8.3609	8.2723
Alt. 1	472.51	545.85	686.94	1.215	1.810	2.836	22.16	35.14	70.19	8.4150	8.3610	8.2725

Alternative	CO_2 Concentration (ppm)			Global Mean Surface Temperature Increase (°C)[b]			Sea-Level Rise (cm)[b]			Ocean pH[c]		
	2040	2060	2100	2040	2060	2100	2040	2060	2100	2040	2060	2100
Alt. 2	472.48	545.76	686.73	1.215	1.809	2.835	22.16	35.14	70.17	8.4150	8.3610	8.2726
Alt. 3	472.45	545.67	686.55	1.215	1.809	2.834	22.16	35.14	70.15	8.4150	8.3611	8.2727
Reductions Under Alternatives												
Alt. 1	0.05	0.15	0.35	0.000	0.001	0.002	0.00	0.01	0.03	-0.0000	-0.0001	-0.0002
Alt. 2	0.08	0.25	0.56	0.000	0.001	0.003	0.00	0.01	0.05	-0.0001	-0.0002	-0.0003
Alt. 3	0.11	0.33	0.74	0.001	0.002	0.003	0.00	0.02	0.07	-0.0001	-0.0002	-0.0004

Notes:
[a] The numbers in this table have been rounded for presentation purposes. As a result, the reductions might not reflect the exact difference of the values in all cases.
[b] The values for global mean surface temperature and sea-level rise are relative to the average of the years 1986–2005.
[c] Ocean pH changes reported as 0.0000 are less than zero but more than -0.0001.
CO_2 = carbon dioxide; ppm = parts per million; °C = degrees Celsius; cm = centimeters

Atmospheric Carbon Dioxide Concentrations

As Figure 8.6.4-1 and Figure 8.6.4-2 show, the reductions in projected CO_2 concentrations under the Proposed Action and alternatives compared to the No Action Alternative amount to a small fraction of the projected total increases in CO_2 concentrations. However, the relative impact of the action alternatives is demonstrated by the reductions of CO_2 concentrations under the range of action alternatives compared to the No Action Alternative. As shown in Figure 8.6.4-2, the reduction in CO_2 concentrations by 2100 under Alternative 3 compared to the No Action Alternative is more than twice that of Alternative 1 compared to the No Action Alternative.

Figure [STYLEREF 3 \s]-[SEQ Figure * ARABIC \s 3]. Atmospheric Carbon Dioxide Concentrations by Alternative

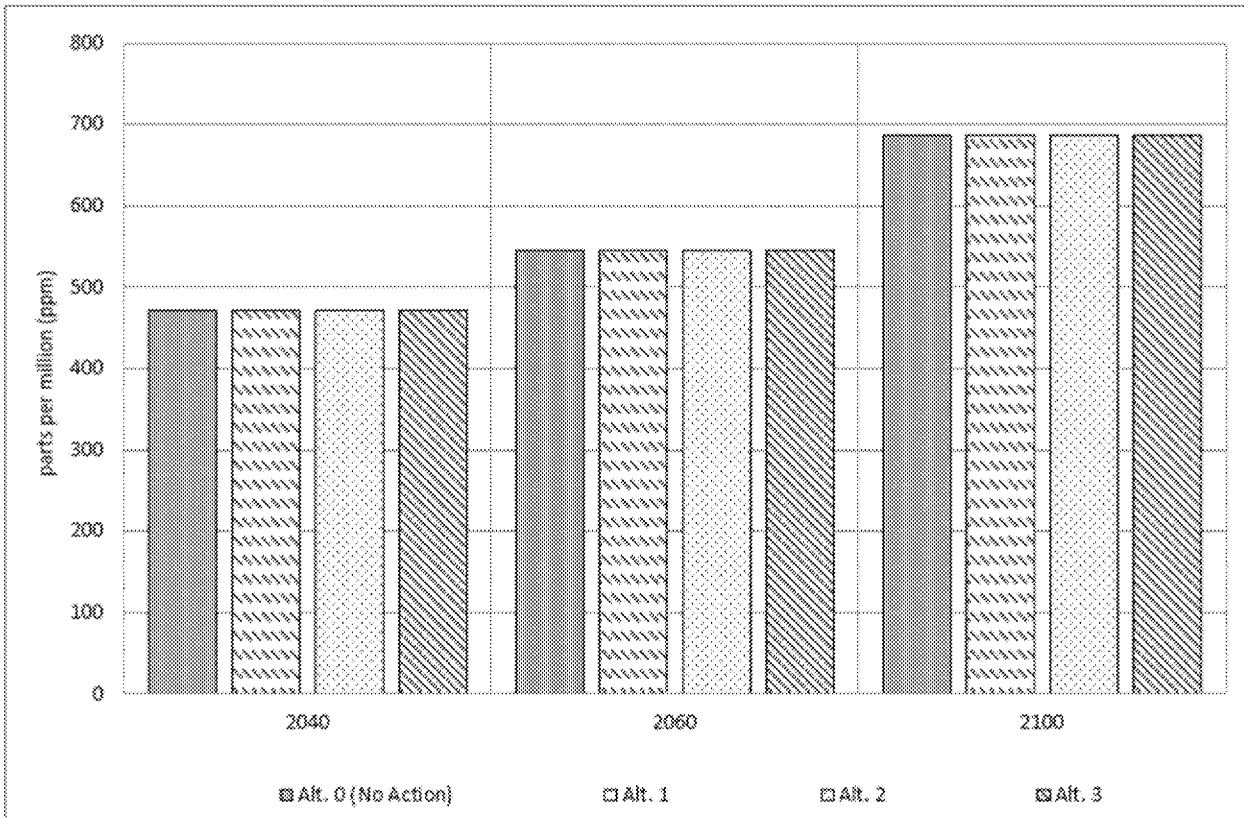
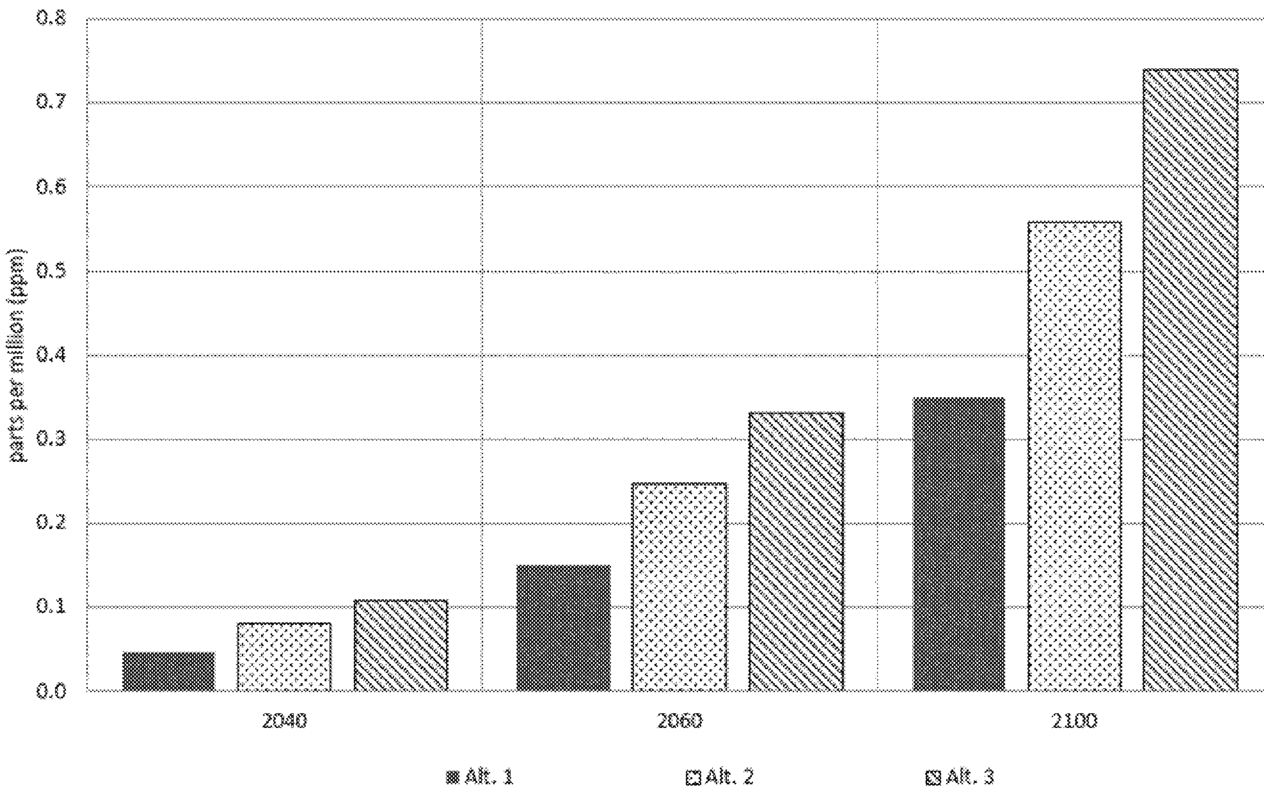


Figure [STYLEREF 3 \s]-[SEQ Figure * ARABIC \s 3]. Reductions in Atmospheric Carbon Dioxide Concentrations Compared to the No Action Alternative



Temperature

MAGICC simulations of mean global surface air temperature increases are shown in Figure 8.6.4-3 and Figure 8.6.4-4. Under the No Action Alternative, assuming an emissions scenario that considers moderate global success in reducing GHG emissions, the cumulative global mean surface temperature is projected to increase by 1.216°C (2.189°F) by 2040, 1.810°C (3.260°F) by 2060, and 2.838°C (5.108°F) by 2100.[18] The differences among alternatives are small (Figure 8.6.4-3). For example, in 2100, the decrease in temperature under the action alternatives would range from approximately 0.002°C (0.003°F) under Alternative 1 to 0.003°C (0.006°F) under Alternative 3. Quantifying the changes to regional climate from this rulemaking is not possible because of the limitations of existing climate models. However, the action alternatives would be expected to reduce the changes in regional temperatures roughly in proportion to the reduction in global mean surface temperature. Regional changes to warming and seasonal temperatures as described in the IPCC Fifth Assessment Report are summarized in Table 5.4.2-3.

[18] Because the actual increase in global mean surface temperature lags the commitment to warming, the impact on global mean surface temperature increase is less than the impact on the long-term commitment to warming. The actual increase in surface temperature lags the commitment due primarily to the time required to heat the oceans.

Figure [STYLEREF 3 \s]-[SEQ Figure * ARABIC \s 3]. Global Mean Surface Temperature Increase by Alternative

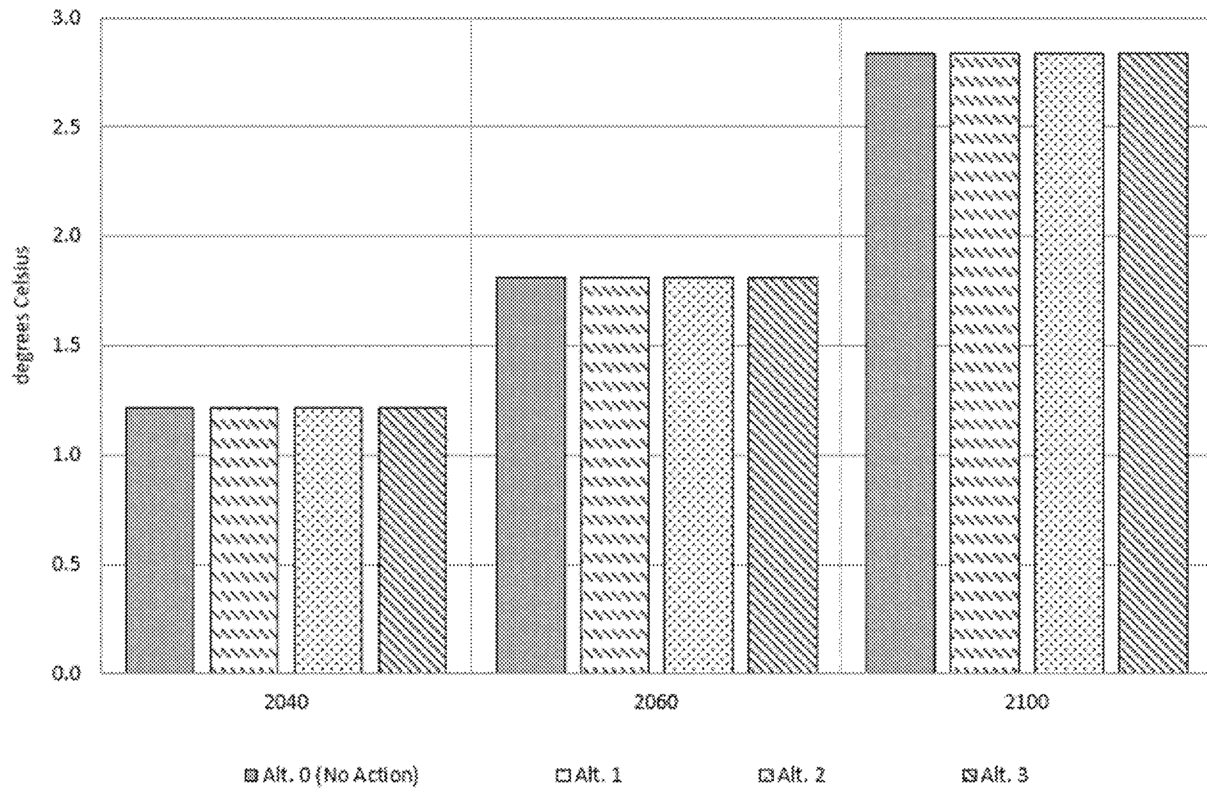
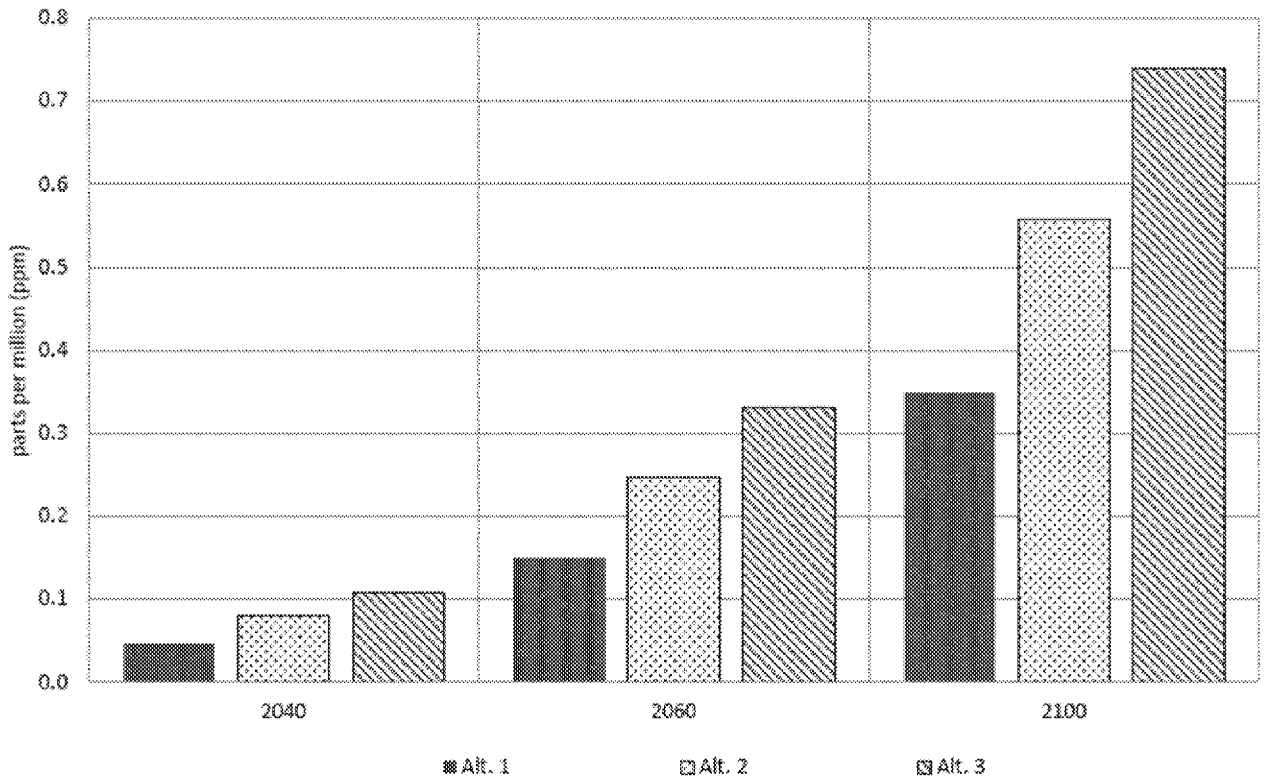


Figure [STYLEREF 3 \s]-[SEQ Figure * ARABIC \s 3]. Reductions in Global Mean Surface Temperature Compared to the No Action Alternative



Precipitation

The effects of higher temperatures on the amount of precipitation and the intensity of precipitation events, as well as the IPCC scaling factors to estimate global mean precipitation change, are discussed in Section 5.4.2.2, *Climate Change Attributes, Precipitation*. Applying these scaling factors to the increase in global mean surface warming provides estimates of changes in global mean precipitation. Given that the Proposed Action and alternatives would reduce temperatures slightly compared to the No Action Alternative, they also would reduce predicted increases in precipitation slightly; however, as shown in Table 8.6.4-2, the reduction would be less than 0.01 percent in most instances.

Regional variations and changes in the intensity of precipitation events cannot be quantified further. This inability is due primarily to the lack of availability of atmospheric-ocean general circulation models (AOGCMs) required to estimate these changes. AOGCMs are typically used to provide results among scenarios with very large changes in emissions, such as the RCP2.6 (low), RCP4.5 (medium), RCP6.0 (medium-high) and RCP8.5 (high) scenarios; very small changes in emissions profiles produce results that would be difficult to resolve. Also, the various AOGCMs produce results that are regionally consistent in some cases but inconsistent in others.

Table [STYLEREF 3 \s]-[SEQ Table * ARABIC \s 3]. Global Mean Precipitation (Percent Increase) Based on GCAM6.0 Scenario Using Increases in Global Mean Surface Temperature Simulated by MAGICC, by Alternative[a]

Scenario	2040	2060	2100
Global Mean Precipitation Change (scaling factor, % change in precipitation per °C change in temperature)		1.68%	
Global Temperature Above Average 1986–2005 Levels (°C) for the GCAM6.0 Scenario			
Alternative 0 (No Action)	1.216	1.810	2.838
Alternative 1	1.215	1.810	2.836
Alternative 2	1.215	1.809	2.835
Alternative 3	1.215	1.809	2.834
Reductions in Global Temperature (°C) Compared to the No Action Alternative[b]			
Alternative 1	0.000	0.001	0.002
Alternative 2	0.000	0.001	0.003
Alternative 3	0.001	0.002	0.003
Global Mean Precipitation Increase (%)			
Alternative 0 (No Action)	2.04%	3.04%	4.77%
Alternative 1	2.04%	3.04%	4.76%
Alternative 2	2.04%	3.04%	4.76%
Alternative 3	2.04%	3.04%	4.76%
Reductions in Global Mean Precipitation Increase Compared to the No Action Alternative[c]			
Alternative 1	0.00%	0.00%	0.00%
Alternative 2	0.00%	0.00%	0.00%
Alternative 3	0.00%	0.00%	0.01%

Notes:
[a] The numbers in this table have been rounded for presentation purposes. As a result, the reductions might not reflect the exact difference of the values in all cases.
[b] Precipitation changes reported as 0.000 are more than zero but less than 0.001.
[c] The reduction in precipitation is less than 0.005% and thus is rounded to 0.00%.
GCAM = Global Change Assessment Model; MAGICC = Model for the Assessment of Greenhouse-gas Induced Climate Change; °C = degrees Celsius

Quantifying the changes in regional climate that would result from the action alternatives is not possible, but the action alternatives would reduce regional changes in precipitation roughly in proportion to the reductions in global mean precipitation. Regional changes to precipitation as described by the IPCC Fifth Assessment Report are summarized in Table 5.4.2-6.

Sea-Level Rise

The components of sea-level rise, treatment of these components, and recent scientific assessments are discussed in Section 5.4.2.2, *Sea-Level Rise*. Table 8.6.4-1 presents the cumulative impact on sea-level rise from each alternative and show sea-level rise in 2100 ranging from 70.22 centimeters (27.65 inches) under the No Action Alternative to 70.15 centimeters (27.62 inches) under Alternative 3, for a maximum decrease of 0.07 centimeter (0.03 inch) by 2100.

Ocean pH

Table 8.6.4-1 shows the projected increase of ocean pH under each action alternative compared to the No Action Alternative. Ocean pH under the alternatives ranges from 8.2723 under the No Action Alternative to 8.2727 under Alternative 3, for a maximum increase in pH of 0.0004 by 2100.

Climate Sensitivity Variations

NHTSA examined the sensitivity of climate impacts on key assumptions used in the analysis. This examination reviewed the impact of various climate sensitivities and global emissions scenarios on the climate effects of three of the alternatives—the No Action Alternative, Alternative 1, and Alternative 3. This range of alternatives was deemed sufficient to assess the effect of various climate sensitivities on the results. Table 8.6.4-3 presents the results of the sensitivity analysis for cumulative impacts.

Table [STYLEREF 3 \s]-[SEQ Table * ARABIC \s 3]. Carbon Dioxide Concentrations, Global Mean Surface Temperature Increases, Sea-Level Rise,[a] and Ocean pH for RCP4.5 for Selected Alternatives[b]

Alternative	Climate Sensitivity (°C for 2 × CO_2)	CO_2 Concentration (ppm)			Global Mean Surface Temperature Increase (°C)[c]			Sea-Level Rise (cm)[c]	Ocean pH
		2040	2060	2100	2040	2060	2100	2100	2100
Alt. 0 (No Action)	1.5	454.05	494.89	510.15	0.619	0.859	1.040	31.58	8.3864
	2.0	457.30	500.90	521.85	0.793	1.114	1.389	40.80	8.3779
	2.5	460.23	506.45	533.11	0.952	1.352	1.729	50.33	8.3699
	3.0	462.88	511.57	543.93	1.097	1.573	2.059	60.04	8.3623
	4.5	469.44	524.72	573.71	1.464	2.152	2.978	89.27	8.3421
	6.0	474.49	535.31	599.95	1.752	2.627	3.797	117.62	8.3250
Alt. 1	1.5	454.00	494.74	509.86	0.618	0.858	1.039	31.56	8.3866
	2.0	457.25	500.76	521.54	0.793	1.113	1.387	40.77	8.3781
	2.5	460.19	506.30	532.80	0.951	1.351	1.728	50.31	8.3701
	3.0	462.84	511.42	543.61	1.097	1.572	2.057	60.01	8.3625
	4.5	469.40	524.57	573.37	1.463	2.151	2.975	89.21	8.3423
	6.0	474.44	535.15	599.59	1.751	2.625	3.794	117.55	8.3252
Alt. 2	1.5	453.97	494.65	509.69	0.618	0.858	1.038	31.55	8.3868
	2.0	457.22	500.67	521.36	0.792	1.113	1.387	40.76	8.3783
	2.5	460.15	506.21	532.62	0.951	1.350	1.727	50.29	8.3702
	3.0	462.80	511.33	543.42	1.097	1.572	2.056	59.99	8.3626
	4.5	469.36	524.47	573.17	1.463	2.150	2.974	89.18	8.3424
	6.0	474.41	535.06	599.38	1.751	2.625	3.792	117.50	8.3253
Alt. 3	1.5	453.94	494.57	509.53	0.618	0.857	1.037	31.54	8.3869
	2.0	457.19	500.58	521.21	0.792	1.112	1.386	40.75	8.3784
	2.5	460.13	506.13	532.45	0.951	1.350	1.726	50.27	8.3703
	3.0	462.77	511.25	543.26	1.096	1.571	2.055	59.97	8.3628
	4.5	469.33	524.39	572.99	1.463	2.149	2.972	89.15	8.3425
	6.0	474.38	534.97	599.19	1.751	2.624	3.790	117.46	8.3254

Alternative	Climate Sensitivity (°C for 2 × CO_2)	CO_2 Concentration (ppm)			Global Mean Surface Temperature Increase (°C)[c]			Sea-Level Rise (cm)[c]	Ocean pH
		2040	2060	2100	2040	2060	2100	2100	2100
Reductions Under Alternative 1 Compared to the No Action Alternative									
Alt. 1	1.5	0.05	0.14	0.29	0.000	0.001	0.001	0.02	-0.0002
	2.0	0.05	0.15	0.30	0.000	0.001	0.001	0.02	-0.0002
	2.5	0.05	0.15	0.31	0.000	0.001	0.002	0.03	-0.0002
	3.0	0.05	0.15	0.32	0.000	0.001	0.002	0.04	-0.0002
	4.5	0.05	0.15	0.34	0.000	0.001	0.002	0.05	-0.0002
	6.0	0.05	0.15	0.36	0.000	0.001	0.003	0.07	-0.0002
Reductions Under Alternative 2 Compared to the No Action Alternative									
Alt. 2	1.5	0.08	0.24	0.47	0.000	0.001	0.002	0.03	-0.0003
	2.0	0.08	0.24	0.48	0.000	0.001	0.002	0.04	-0.0003
	2.5	0.08	0.24	0.50	0.000	0.001	0.003	0.05	-0.0004
	3.0	0.08	0.24	0.51	0.000	0.001	0.003	0.06	-0.0004
	4.5	0.08	0.25	0.55	0.000	0.002	0.004	0.09	-0.0004
	6.0	0.08	0.25	0.58	0.000	0.002	0.005	0.12	-0.0004
Reductions Under Alternative 3 Compared to the No Action Alternative									
Alt. 3	1.5	0.11	0.32	0.62	0.000	0.001	0.002	0.03	-0.0005
	2.0	0.11	0.32	0.64	0.000	0.001	0.003	0.05	-0.0005
	2.5	0.11	0.32	0.66	0.000	0.002	0.003	0.06	-0.0005
	3.0	0.11	0.32	0.68	0.001	0.002	0.004	0.08	-0.0005
	4.5	0.11	0.33	0.72	0.001	0.002	0.005	0.12	-0.0005
	6.0	0.11	0.34	0.77	0.001	0.003	0.006	0.16	-0.0005

Notes:
[a] Sea-level rise results are based on the regression analysis described in Section 5.3.3, *Methods for Estimating Climate Effects*.
[b] The numbers in this table have been rounded for presentation purposes. As a result, the reductions do not reflect the exact difference of the values.
[c] The values for global mean surface temperature and sea-level rise are relative to the average of the years 1986–2005.
ppm = parts per million; °C = degrees Celsius; CO_2 = carbon dioxide; cm = centimeters; RCP = Representative Concentration Pathways

The use of alternative global emissions scenarios can influence the results in several ways. Emissions reductions under higher emissions scenarios can lead to larger reductions in CO_2 concentrations in later years. Under higher emissions scenarios, anthropogenic emissions levels exceed global emissions sinks (e.g., plants, oceans, and soils) by a greater extent. As a result, emissions reductions under higher emissions scenarios are avoiding more of the anthropogenic emissions that are otherwise expected to stay in the atmosphere (are not removed by sinks) and contribute to higher CO_2 concentrations. The use of different climate sensitivities (the equilibrium warming that occurs at a doubling of CO_2 from preindustrial levels) could affect not only projected warming but also indirectly affect projected sea-level rise, CO_2 concentration, and ocean pH. Sea level is influenced by temperature. CO_2 concentration and ocean pH are affected by temperature-dependent effects of ocean carbon storage (higher temperature results in lower aqueous solubility of CO_2).

As shown in Table 8.6.4-4 and Table 8.6.4-5, the sensitivity of simulated CO_2 emissions in 2040, 2060, and 2100 to assumptions of global emissions and climate sensitivity is low; the incremental changes in CO_2 concentration (i.e., the difference between Alternative 3 and Alternative 1) are insensitive to different assumptions on global emissions and climate sensitivity. For 2040 and 2060, the choice of global emissions scenario has little impact on the results. By 2100, the action alternatives would have the greatest impact on CO_2 concentration in the global emissions scenario with the highest CO_2 emissions (GCAM Reference scenario), and the least impact in the scenario with the lowest CO_2 emissions (RCP4.5). The total range of the impact of Alternative 3 on CO_2 concentrations in 2100 is roughly 0.68 to 0.77 ppm across all three global emissions scenarios. Alternative 3, using the GCAM6.0 scenario and a 3.0°C (5.4°F) climate sensitivity, would have a 0.74 ppm decrease compared to Alternative 1, which would have a 0.35 ppm decrease in 2100.

Table [STYLEREF 3 \s]-[SEQ Table * ARABIC \s 3]. Carbon Dioxide Concentrations, Global Mean Surface Temperature Increases, Sea-Level Rise,[a] and Ocean pH for GCAM6.0[a] for Selected Alternatives[b]

Alternative	Climate Sensitivity (°C for 2 × CO_2)	CO_2 Concentration (ppm)			Global Mean Surface Temperature Increase (°C)[c]			Sea-Level Rise (cm)[c]	Ocean pH
		2040	2060	2100	2040	2060	2100	2100	2100
Alt. 0 (No Action)	1.5	463.33	527.73	643.45	0.694	1.005	1.506	36.94	8.2980
	2.0	466.74	534.33	658.72	0.885	1.294	1.971	47.83	8.2889
	2.5	469.80	540.41	673.33	1.058	1.562	2.415	58.97	8.2803
	3.0	472.56	546.00	687.29	1.216	1.810	2.838	70.22	8.2723
	4.5	479.39	560.37	725.55	1.611	2.456	3.998	103.79	8.2510
	6.0	484.62	571.96	759.36	1.920	2.984	5.037	136.36	8.2329
Alt. 1	1.5	463.28	527.58	643.12	0.694	1.004	1.505	36.93	8.2982
	2.0	466.69	534.18	658.39	0.885	1.294	1.970	47.81	8.2890
	2.5	469.75	540.26	672.99	1.058	1.561	2.413	58.94	8.2805
	3.0	472.51	545.85	686.94	1.215	1.810	2.836	70.19	8.2725
	4.5	479.34	560.22	725.17	1.611	2.455	3.996	103.74	8.2512
	6.0	484.58	571.80	758.96	1.920	2.983	5.034	136.29	8.2331
Alt. 2	1.5	463.25	527.49	642.93	0.694	1.004	1.505	36.92	8.2983
	2.0	466.66	534.09	658.19	0.885	1.293	1.969	47.79	8.2892
	2.5	469.72	540.16	672.78	1.058	1.561	2.413	58.93	8.2806
	3.0	472.48	545.76	686.73	1.215	1.809	2.835	70.17	8.2726
	4.5	479.30	560.12	724.95	1.611	2.454	3.995	103.71	8.2513
	6.0	484.54	571.70	758.74	1.920	2.982	5.033	136.25	8.2332
Alt. 3	1.5	463.22	527.41	642.77	0.694	1.004	1.504	36.91	8.2984
	2.0	466.63	534.01	658.02	0.885	1.293	1.969	47.78	8.2893
	2.5	469.69	540.08	672.61	1.058	1.561	2.412	58.91	8.2807
	3.0	472.45	545.67	686.55	1.215	1.809	2.834	70.15	8.2727
	4.5	479.28	560.03	724.76	1.611	2.453	3.993	103.68	8.2514
	6.0	484.51	571.61	758.53	1.920	2.982	5.031	136.21	8.2334
Reductions Under Alternative 1 Compared to the No Action Alternative									

Alternative	Climate Sensitivity (°C for 2 × CO_2)	CO_2 Concentration (ppm)			Global Mean Surface Temperature Increase (°C)[c]			Sea-Level Rise (cm)[c]	Ocean pH
		2040	2060	2100	2040	2060	2100	2100	2100
Alt. 1	1.5	0.05	0.15	0.32	0.000	0.000	0.001	0.02	-0.0002
	2.0	0.05	0.15	0.33	0.000	0.001	0.001	0.02	-0.0002
	2.5	0.05	0.15	0.34	0.000	0.001	0.001	0.03	-0.0002
	3.0	0.05	0.15	0.35	0.000	0.001	0.002	0.03	-0.0002
	4.5	0.05	0.15	0.37	0.000	0.001	0.002	0.05	-0.0002
	6.0	0.05	0.16	0.40	0.000	0.001	0.003	0.07	-0.0002
Reductions Under Alternative 2 Compared to the No Action Alternative									
Alt. 2	1.5	0.08	0.24	0.51	0.000	0.001	0.001	0.02	-0.0003
	2.0	0.08	0.24	0.53	0.000	0.001	0.002	0.03	-0.0003
	2.5	0.08	0.24	0.54	0.000	0.001	0.002	0.04	-0.0003
	3.0	0.08	0.25	0.56	0.000	0.001	0.003	0.05	-0.0003
	4.5	0.08	0.25	0.59	0.000	0.002	0.003	0.08	-0.0003
	6.0	0.08	0.26	0.63	0.000	0.002	0.004	0.11	-0.0003
Reductions Under Alternative 3 compared to the No Action Alternative									
Alt. 3	1.5	0.11	0.32	0.68	0.000	0.001	0.002	0.03	-0.0004
	2.0	0.11	0.33	0.70	0.000	0.001	0.003	0.05	-0.0004
	2.5	0.11	0.33	0.72	0.000	0.002	0.003	0.06	-0.0004
	3.0	0.11	0.33	0.74	0.001	0.002	0.003	0.07	-0.0004
	4.5	0.11	0.34	0.79	0.001	0.002	0.005	0.11	-0.0004
	6.0	0.11	0.34	0.83	0.001	0.002	0.006	0.15	-0.0004

Notes:
[a] Sea-level rise results are based on the regression analysis described in Section 5.3.3, *Methods for Estimating Climate Effects*, using GCAM6.0.
[b] The numbers in this table have been rounded for presentation purposes. As a result, the reductions do not reflect the exact difference of the values.
[c] The values for global mean surface temperature and sea-level rise are relative to the average of the years 1986–2005.
ppm = parts per million; °C = degrees Celsius; CO_2 = carbon dioxide; cm = centimeters; GCAM = Global Change Assessment Model

Table [STYLEREF 3 \s]-[SEQ Table * ARABIC \s 3]. Carbon Dioxide Concentrations, Global Mean Surface Temperature Increases, Sea-Level Rise,[a] and Ocean pH for GCAM Reference for Selected Alternatives[b]

Alternative	Climate Sensitivity (°C for 2 × CO_2)	CO_2 Concentration (ppm)			Global Mean Surface Temperature Increase (°C)[b]			Sea Level Rise (cm)[c]	Ocean pH
		2040	2060	2100	2040	2060	2100	2100	2100
Alt. 0 (No Action)	1.5	469.61	546.10	737.48	0.741	1.128	1.890	41.05	8.2445
	2.0	473.09	553.09	755.49	0.941	1.446	2.451	52.74	8.2350
	2.5	476.22	559.52	772.69	1.123	1.738	2.981	64.52	8.2260

Alternative	Climate Sensitivity (°C for 2 × CO_2)	CO_2 Concentration (ppm)			Global Mean Surface Temperature Increase (°C)[b]			Sea Level Rise (cm)[c]	Ocean pH
		2040	2060	2100	2040	2060	2100	2100	2100
	3.0	479.04	565.44	789.11	1.287	2.008	3.484	76.28	8.2176
	4.5	486.00	580.62	834.28	1.699	2.707	4.868	110.93	8.1952
	6.0	491.34	592.87	874.88	2.020	3.279	6.171	144.70	8.1759
Alt. 1	1.5	469.56	545.95	737.14	0.741	1.128	1.889	41.03	8.2447
	2.0	473.04	552.94	755.14	0.941	1.445	2.450	52.72	8.2351
	2.5	476.17	559.37	772.33	1.122	1.738	2.980	64.50	8.2262
	3.0	478.99	565.29	788.74	1.287	2.007	3.483	76.25	8.2178
	4.5	485.95	580.47	833.90	1.699	2.706	4.866	110.89	8.1954
	6.0	491.29	592.72	874.45	2.019	3.278	6.168	144.64	8.1761
Alt. 2	1.5	469.53	545.85	736.95	0.740	1.127	1.889	41.02	8.2448
	2.0	473.01	552.85	754.94	0.941	1.445	2.449	52.71	8.2352
	2.5	476.14	559.27	772.12	1.122	1.737	2.979	64.48	8.2263
	3.0	478.96	565.19	788.52	1.287	2.007	3.482	76.23	8.2179
	4.5	485.92	580.37	833.65	1.698	2.705	4.865	110.86	8.1955
	6.0	491.26	592.61	874.21	2.019	3.277	6.167	144.59	8.1763
Alt. 3	1.5	469.50	545.77	736.77	0.740	1.127	1.888	41.01	8.2449
	2.0	472.98	552.76	754.76	0.941	1.445	2.449	52.70	8.2353
	2.5	476.11	559.19	771.94	1.122	1.737	2.978	64.47	8.2264
	3.0	478.93	565.11	788.33	1.287	2.007	3.481	76.22	8.2180
	4.5	485.89	580.28	833.45	1.698	2.705	4.864	110.83	8.1956
	6.0	491.23	592.53	873.98	2.019	3.277	6.165	144.56	8.1764
Reductions Under Alternative 1 Compared to the No Action Alternative									
Alt. 1	1.5	0.05	0.15	0.34	0.000	0.000	0.001	0.01	-0.0002
	2.0	0.05	0.15	0.35	0.000	0.001	0.001	0.02	-0.0002
	2.5	0.05	0.15	0.36	0.000	0.001	0.001	0.02	-0.0002
	3.0	0.05	0.15	0.37	0.000	0.001	0.002	0.03	-0.0002
	4.5	0.05	0.16	0.37	0.000	0.001	0.002	0.05	-0.0002
	6.0	0.05	0.16	0.43	0.000	0.001	0.003	0.06	-0.0002
Reductions Under Alternative 2 Compared to the No Action Alternative									
Alt. 2	1.5	0.08	0.24	0.54	0.000	0.001	0.001	0.02	-0.0003
	2.0	0.08	0.25	0.55	0.000	0.001	0.002	0.03	-0.0003
	2.5	0.08	0.25	0.57	0.000	0.001	0.002	0.04	-0.0003
	3.0	0.08	0.25	0.58	0.000	0.001	0.002	0.05	-0.0003
	4.5	0.08	0.25	0.62	0.000	0.002	0.003	0.08	-0.0003
	6.0	0.08	0.26	0.67	0.000	0.002	0.005	0.11	-0.0003
Reductions Under Alternative 3 Compared to the No Action Alternative									
Alt. 3	1.5	0.11	0.32	0.71	0.000	0.001	0.002	0.03	-0.0004
	2.0	0.11	0.33	0.73	0.000	0.001	0.002	0.04	-0.0004
	2.5	0.11	0.33	0.75	0.000	0.001	0.003	0.05	-0.0004

Alternative	Climate Sensitivity (°C for 2 × CO_2)	CO_2 Concentration (ppm)			Global Mean Surface Temperature Increase (°C)[b]			Sea Level Rise (cm)[c]	Ocean pH
		2040	2060	2100	2040	2060	2100	2100	2100
	3.0	0.11	0.33	0.77	0.001	0.002	0.003	0.06	-0.0004
	4.5	0.11	0.34	0.83	0.001	0.002	0.004	0.10	-0.0004
	6.0	0.11	0.35	0.91	0.001	0.002	0.006	0.14	-0.0004

Notes:
[a] Sea-level rise results are based on the regression analysis described in Section 5.3.3, *Methods for Estimating Climate Effects*, using a hybrid relation based on RCP6.0 and RCP8.5.
[b] The numbers in this table have been rounded for presentation purposes. As a result, the reductions do not reflect the exact difference of the values.
[c] The values for global mean surface temperature and sea-level rise are relative to the average of the years 1986-2005.
ppm = parts per million; °C = degrees Celsius; CO_2 = carbon dioxide; cm = centimeters; GCAM = Global Change Assessment Model

The sensitivity of the simulated global mean surface temperatures for 2040, 2060, and 2100 varies over the simulation period, as shown in Table 8.6.4-5. In 2040, the impact would be low due primarily to the rate at which global mean surface temperature increases in response to increases in radiative forcing. In 2100, the impact would be larger due to climate sensitivity and change in emissions. The impact on global mean surface temperature due to assumptions concerning global emissions of GHGs is also important. When using modeling using the GCAM Reference scenario (the scenario with the highest global emissions of GHGs), Alternative 3 has a greater reduction in global mean surface temperature than when modeled under RCP4.5 (the scenario with lowest global emissions). This is due to the nonlinear and near-logarithmic relationship between radiative forcing and CO_2 concentrations. At high emissions levels, CO_2 concentrations are high; therefore, a fixed reduction in emissions yields a greater reduction in radiative forcing and global mean surface temperature.

The sensitivity of simulated sea-level rise to change in climate sensitivity and global GHG emissions mirrors that of global temperature, as shown in Table 8.6.4-3 through Table 8.6.4-5. Scenarios with lower climate sensitivities have lower increases in sea-level rise; the increase in sea-level rise is lower under each alternative than it would be under scenarios with higher climate sensitivities. Conversely, scenarios with higher climate sensitivities have higher sea-level rise; the increase of sea-level rise would be higher under the action alternatives than it would be under scenarios with lower climate sensitivities. Higher global GHG emissions scenarios have higher sea-level rise, but the impact of the action alternatives would be less than in scenarios with lower global emissions. Conversely, scenarios with lower global GHG emissions have lower sea-level rise, although the impact of the action alternatives is greater than in scenarios with higher global emissions.

The sensitivity of the simulated ocean pH to change in climate sensitivity and global GHG emissions is low, and less than that of global CO_2 concentrations.

8.6.5 Health, Societal, and Environmental Impacts of Climate Change

8.6.5.1 Introduction

As described in Section 5.4, *Environmental Consequences*, and Section 8.6.4, *Cumulative Impacts on Greenhouse Gas Emissions and Climate Change,* ongoing emissions of GHGs from many sectors, including transportation, affect global CO_2 concentrations, temperature, precipitation, sea level, and ocean pH. This section describes how these effects can translate to impacts on key natural and human resources.

Although the action alternatives would decrease the growth in GHG emissions as discussed in Section 5.4 and Section 8.6.4, they alone would not prevent climate change. Instead, the action alternatives would reduce anticipated increases of global CO_2 concentrations and associated impacts, including changes in temperature, precipitation, sea level, and ocean pH that are otherwise projected to occur under the No Action Alternative. Similarly, to the extent the action alternatives would result in reductions in projected increases in global CO_2 concentrations, this rulemaking would also reduce the impact of climate change across resources and the risk of crossing atmospheric CO_2 concentration thresholds that trigger abrupt changes in Earth's systems—thresholds known as "tipping points." NHTSA's assumption is that reductions in climate effects relating to temperature, precipitation, sea level, and ocean pH would decrease impacts on affected resources described in this section. However, the climate change impacts of the Proposed Action and alternatives would be too small to address quantitatively in terms of impacts on the specific resources.[19] Consequently, the discussion of resource impacts in this section does not distinguish between the alternatives; rather, it provides a qualitative review of projected impacts (where the potential benefits of reducing GHG emissions would result in reducing in these impacts). This section also briefly describes ongoing efforts to adapt to climate change to increase the resilience of human and natural systems to the adverse risks of such change.

The health, societal, and environmental impacts are discussed in two parts: Section 8.6.5.2, *Sectoral Impacts of Climate Change*, discusses the sector-specific impacts of climate change, while Section 8.6.5.3, *Regional Impacts of Climate Change*, discusses the region-specific impacts of climate change.

8.6.5.2 Sectoral Impacts of Climate Change

This section discusses how climate change resulting from global GHG emissions (including the U.S. light-duty transportation sector under the Proposed Action and alternatives) could affect certain key natural and human resources: freshwater resources; terrestrial and freshwater ecosystems; ocean systems, coasts, and low-lying areas; food, fiber, and forest products; urban areas; rural areas; human health; human security; and stratospheric ozone. In addition, this section discusses compound events, tipping points, and abrupt climate change.

NHTSA's analysis draws largely from recent studies and reports, including the IPCC *Fifth Assessment Report* (IPCC 2013a, 2013b, 2014a, 2014b, 2014d), the IPCC *Special Study: Global Warming of 1.5° C* (IPCC 2018), the IPCC *Special Report on the Ocean and Cryosphere in a Changing Climate* (IPCC 2019a), the IPCC *Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems* (IPCC 2019b), and the Global Climate Research Program (GCRP) *National Climate Assessment* (NCA) *Reports* (GCRP 2014, 2017, 2018a). The IPCC and GCRP reports, in particular, provide a comprehensive overview of the state of scientific, technical, and socioeconomic knowledge on climate change, its causes, and its potential impacts. To reflect the likelihood of climate change impacts accurately for each sector, NHTSA references and uses the IPCC uncertainty guidelines (Section 5.1.1, *Uncertainty within the IPCC Framework*). This approach provides a consistent method to define confidence levels and percent

[19] Additionally, it is inappropriate to identify increases in GHG emissions associated with a single source or group of sources as the single cause of any particular climate-related impact or event.

probability of a projected outcome or impact. This is primarily applied for key IPCC and GCRP findings where IPCC or GCRP has defined the associated uncertainty with the finding (other sources generally do not provide enough information or expert consensus to elicit uncertainty rankings).

Recent reports from GCRP and such agencies as the National Research Council (NRC) are also referenced in this chapter. NHTSA relies on major international or national scientific assessment reports because these reports have assessed numerous individual studies to draw general conclusions about the potential impacts of climate change. This material has been well vetted, both by the climate change research community and by the U.S. government. In addition, NHTSA has supplemented the findings from these reports with recent peer-reviewed information, as appropriate.

Freshwater Resources

This section provides an overview of the recent findings regarding observed and projected impacts of climate change on freshwater resources in the United States and globally. More than 70 percent of the surface of the Earth is covered by water, but only 2.5 percent is fresh water. Respectively, freshwater contributions include permanent snow cover in the Antarctic, the Arctic, and mountainous regions (68.7 percent); groundwater (29.9 percent); and fresh water in lakes, reservoirs, and river systems (0.26 percent) (UNESCO 2006).

Potential risks to freshwater resources are expected to increase with increasing GHG emissions; for example, higher emissions are projected to result in less renewable water at the same time as continued population growth (IPCC 2014b). Although some positive impacts are anticipated, including reductions in water stress and increases in water quality in some areas because of increased runoff, the negative impacts are expected to outweigh positive impacts (IPCC 2014b; GCRP 2014, 2018a).

Observed and Projected Climate Impacts

In recent decades, annual average precipitation increases have been observed across the Midwest, Great Plains, Northeast, and Alaska, while decreases have been observed in Hawaii, the Southeast and the Southwest (GCRP 2017; Walsh et al. 2014; Huang et al. 2017). Nationally, there has been an average increase of 4 percent in annual precipitation from 1901 to 2016 (GCRP 2017). According to GCRP, globally, for mid-latitude land areas of the Northern Hemisphere, annual average precipitation has *likely* increased since 1901 (GCRP 2017). For most other latitudinal zones, long-term trends in average precipitation are uncertain due to data quality, data completeness, or disagreement among available estimates (IPCC 2014d).

Detected trends in streamflow and runoff are generally consistent with observed regional changes in precipitation and temperature (IPCC 2014b). Globally, in regions with seasonal snow storage, warming has led to earlier occurrence of the maximum streamflows from snowmelt during the spring and increased winter streamflows because more winter precipitation falls as rain instead of snow (IPCC 2014b citing Clow 2010, Korhonen and Kuusisto 2010, Tan et al. 2011). These reduced snow-to-rain ratios are leading to significant differences between the timing of water supply and demand (*medium confidence)*. In particular, warming temperatures and reduced snowpack are decreasing surface and groundwater availability in much of the western United States (U.S. Bureau of Reclamation 2021). Changes in the timing of flows and temperatures of freshwater bodies *likely* impact local wildlife populations through phenological and distribution/range shifts (*high confidence*) (GCRP 2018a). Average global precipitation is projected to increase over the next century; generally, wet places are expected to get wetter and dry places are expected to get drier (IPCC 2014d).

The number and intensity of very heavy precipitation events have been increasing significantly across most of the United States (U.S. Bureau of Reclamation 2011). According to the NCA report, river floods have been increasing in parts of the central United States (GCRP 2017). However, GCRP (2017) cites IPCC AR5 (2013a) in concluding that there are no detectable changes in observed flooding magnitude, duration, or frequency in the United States. There is limited evidence that anthropogenic climate change has affected the frequency and magnitude of floods at a global scale (Kundzewicz et al. 2013).

The frequency and magnitude of the heaviest precipitation events is projected to increase everywhere in the United States (GCRP 2017 citing Janssen et al. 2014; U.S. Bureau of Reclamation 2011; GCRP 2014 citing Kharin et al. 2013). Floods that are closely tied to heavy precipitation events, such as flash floods and urban floods, as well as coastal floods related to sea-level rise and the resulting increase in storm surge height and inland impacts, are expected to increase (GCRP 2014). Across a range of emissions scenarios and models, flooding could intensify in many U.S. regions by the 2050s, even in areas where total precipitation is projected to decline (U.S. Bureau of Reclamation 2011, 2016). There is *medium confidence* that global warming of 1.5°C would lead to a lesser expansion of the area with significant increases in runoff than under a 2°C increase (IPCC 2018).

The risk faced from heavy precipitation and flooding events is compounded by aging water infrastructure such as dams and levees across the United States. The scope of the nation's exposure to this risk has not yet been fully identified; however, the estimated reconstruction and maintenance costs for the totality of American water infrastructure is estimated in the trillions of dollars (GCRP 2018a). It can be said with *high confidence* that extreme precipitation events are projected to increase in a warming climate, and that our deteriorating water infrastructure compounds the risk climate change poses to our society (*high confidence*).

In the United States, there is mixed information on the historical connection between climate change and drought. GRCP found that there is little evidence of a human influence on past precipitation shortages (i.e., meteorological or hydrological droughts); however, there is *high confidence* of a human influence on surface soil moisture deficits due to higher temperatures and the resultant increase in evapotranspiration (i.e., agricultural droughts) (GCRP 2017). This increased evapotranspiration has also increased the need for human use of water in many areas. Over the past three decades, efficiency gains in irrigation methods have generally kept pace with this increased usage; however, without further improvements in this area, future human demand could outpace supply in many regions (GCRP 2018a). In fact, due to limitations on surface water storage and trading of water across basins and usages, certain U.S. aquifers have experienced significant depletion (GCRP 2018a citing Russo et al. 2017). Globally, meteorological and agricultural droughts have become more frequent since 1950 in some regions, including southern Europe and western Africa (IPCC 2014b citing Seneviratne et al. 2012). Drought hazards are projected to be less severe at 1.5°C of warming compared to 2°C (IPCC 2018 citing Smirnov et al. 2016, Sun et al. 2017, Arnell et al. 2018, and Liu et al. 2018; IPCC 2019b).

Dry spells are also projected to increase in length in most regions, especially in the southern and northwestern portions of the contiguous United States (EPA 2015c). Projected changes in total average annual precipitation are generally small in many areas, but both wet and dry extremes (heavy precipitation events and length of dry spells) are projected to increase substantially almost everywhere. Long-term (multi-seasonal) drought conditions are also projected to increase in parts of the Southwest (GCRP 2017). Furthermore, trends of earlier spring melt and reduced snow water equivalent are expected to continue, and analyses using higher emissions scenarios project with *high confidence* that the western United States will see chronic, long-duration hydrological droughts (GCRP 2017).

Rising temperatures across the United States have reduced total snowfall, lake ice, seasonal snow cover, sea ice, glaciers, and permafrost over the last few decades (GCRP 2017; EPA 2016e citing Mote and Sharp 2016). Both globally and in the United States, attribution of observed changes in groundwater level, storage, or discharge to climatic changes is difficult due to additional influences of land use changes and groundwater abstractions (IPCC 2014b citing Stoll et al. 2011), and the extent to which groundwater abstractions have already been affected by climate change is not known. Groundwater recharge impacts vary globally (IPCC 2014b citing Allen et al. 2010b, Crosbie et al. 2013b, Ng et al. 2010, and Portmann et al. 2013). Both globally and in the United States, sea-level rise, storms and storm surges, and changes in surface water and groundwater use patterns are expected to compromise the sustainability of coastal freshwater aquifers and wetlands (U.S. Bureau of Reclamation 2016; GCRP 2017). These effects are of particular concern in Hawaii and U.S. territories in the Caribbean and Pacific, threatening previously dependable and safe water supplies. The freshwater supplies in these same areas also face increased potential for contamination from increasingly frequent extreme weather events that damage freshwater infrastructure (GCRP 2018a).

Globally, most observed changes of water quality attributed to climate change are known from isolated, short-term studies, mostly of rivers or lakes in high-income countries. The most frequently reported change is more intense eutrophication (i.e., an increase in phosphorus and nitrogen in freshwater resources) and algal blooms (i.e., excessive growth of algae) at higher temperatures, or shorter hydraulic retention times and higher nutrient loads resulting from increased storm runoff. Changes in the amount of water flow in surface water bodies due to climate change presents chronic problems, such as increased cost of water treatment and greater risk to public health due to pollutant concentrations (GCRP 2018a). Positive reported impacts include reductions in the risk of eutrophication when nutrients were flushed from lakes and estuaries by more frequent storms and hurricanes (IPCC 2014b citing Paerl and Huisman 2008). For rivers, all reported impacts on water quality are negative, and surface water quality as a whole is declining as water temperature increases (*high confidence*) (GCRP 2018a). Studies of impacts on groundwater quality are limited and mostly report elevated concentrations of fecal coliforms during the rainy season or after extreme rain events (IPCC 2014b citing Auld et al. 2004, Curriero et al. 2001, Jean et al. 2006, Seidu et al. 2013, and Tumwine et al. 2002, 2003).

Changes in sediment transport are expected to vary regionally and by land-use type, with potentially large increases in some areas (GCRP 2014 citing Nearing et al. 2005), resulting in alterations to reservoir storage and river channels, affecting flooding, navigation, water supply, and dredging.

Adaptation

Given the uncertainty associated with climate change, adaptation planning often involves anticipatory scenario-based planning and the identification of flexible, low-regrets strategies (e.g., water conservation and demand-side management) to maximize resilience. In the United States and globally, current and projected impacts of climate change on water resources have sparked several responses by water resource managers. In 2011, federal agencies, which manage most of the freshwater resources in the United States, worked with stakeholders to develop a National Action Plan for managing freshwater resources in a changing climate to help ensure adequate freshwater supplies, while also protecting water quality, human health, property, and aquatic ecosystems (ICCATF 2011). Water utilities are determining ways to adjust planning, operational, and capital infrastructure strategies (EPA 2015d; Abt Associates 2016). Water conservation and demand management are also being promoted as important nonstructural, low-regrets approaches for managing water supply.

However, the Fourth National Climate Assessment states that management of surface water and groundwater sources across federal agencies has been hampered by a lack of coordination, creating inefficiencies in the response to climate change. Climate change mitigation policies, if not designed with careful attention to water resources, could increase the magnitude, spatial coverage, and frequency of water deficits given potential increased demand for irrigation water for bioenergy crops (Hejazia et al. 2015).

Terrestrial and Freshwater Ecosystems

This section provides an overview of the recent findings regarding observed and projected impacts of climate change on the terrestrial and freshwater ecosystems in the United States and globally. Ecosystems include all living organisms and their environs that interact as part of a system (GCRP 2014 citing Chapin et al. 2011). These systems are often delicately balanced and sensitive to internal and external pressures due to both human and nonhuman influences. Ecosystems are of concern to society because they provide beneficial ecosystem services such as jobs (e.g., from fisheries and forestry), fertile soils, clean air and water, recreation, and aesthetic value (GCRP 2014 citing Millennium Ecosystem Assessment 2005). Terrestrial and freshwater ecosystems in the United States and around the world are experiencing rapid and observable changes. The ecosystems addressed in this section include terrestrial ecosystems, such as forests, grasslands, shrublands, savanna, and tundra; aquatic ecosystems, such as rivers, lakes, and ponds; and freshwater wetlands, such as marshes, swamps, and bogs.

Observed and Projected Climate Impacts

The impacts of climate change on terrestrial and freshwater ecosystems have been observed at a variety of scales, including individuals (e.g., changes in genetics and physical characteristics), populations (e.g., changes in timing of life cycle events), and species (e.g., changes in geographic range) (GCRP 2018a citing Scheffers et al. 2016). Several reviews of climate change impacts on ecosystem services indicate that 59 to 82 percent of ecosystem services have experienced impacts from climate change (Runting et al. 2016, Scheffers et al. 2016).

Recent global satellite and ground-based data have identified phenology[20] shifts, including earlier spring events such as breeding, budding, flowering, and migration, which have been observed in hundreds of plant and animal species (IPCC 2014b citing Menzel et al. 2006, Cleland et al. 2007, Parmesan 2007, Primack et al. 2009, Cook et al. 2012a, and Peñuelas et al. 2013). In particular, migratory species that rely on one primary food source are particularly vulnerable to climate change due to phenological mismatch (GCRP 2018a citing Both et al. 2010, Mayor et al. 2017, and Ohlberger et al. 2014). In the United States from 1981 to 2010, leaf and bloom events shifted to earlier in the year in northern and western regions, but later in southern regions (EPA 2016f citing Schwartz et al. 2013). Phenological mismatches that result in unfavorable breeding conditions could cause significant negative impacts on species' breeding processes (GCRP 2014 citing Lawler et al. 2010, Todd et al. 2011; Little et al. 2017 citing McNab 2010, Potti 2008; Pecl et. al 2017 citing CAFF 2013, Mustonen 2015). In some ecosystems, higher trophic levels may be more sensitive to climate change than lower trophic levels, which can affect the energy demands and mortality rates of prey, affect overall ecosystem functioning, and alter energy

[20] Phenology refers to the relative timing of species' life-cycle events.

and nutrient flow (GCRP 2018a citing Laws and Joern 2013, McCluney and Sabo 2016, Verdeny-Vilalta and Moya-Laraño 2014, Miller et al. 2014, and Zander et al. 2017).

Species respond to stressors such as climate change by phenotypic[21] or genotypic[22] modifications, migrations, or extinction (IPCC 2014b citing Dawson et al. 2011, Bellard et al. 2012, Peñuelas et al. 2013). Changes in morphology[23] and reproductive rates have been attributed to climate change. For example, the egg sizes of some bird species are changing with increasing regional temperatures (Potti 2008). At least one study indicates that birds in North America are experiencing decreased body size due to changes in climate (Van Buskirk et al. 2010).

Over the past several decades, a pole-ward (in latitude) and upward (in elevation) extension of various species' ranges has been observed that may be attributable to increases in temperature (IPCC 2014b). Climate change has led to range contractions in almost half of studied terrestrial animals and plants in North America (GCRP 2018a citing Wiens 2016). In both terrestrial and freshwater ecosystems, plants and animals are moving up in elevation—at approximately 36 feet per decade—and in latitude—at approximately 10.5 miles per decade (GCRP 2014 citing Chen et al. 2011). Over the 21st century, species range shifts, as well as extirpations, may result in significant changes in ecosystem plant and species mixes, creating entirely new ecosystems (GCRP 2014 citing Staudt et al. 2013, Sabo et al. 2010, Cheung et al. 2009, Lawler et al. 2010, and Stralberg et al. 2009). A recent study suggests that species redistribution is linked to reduced terrestrial productivity, impacts on marine community assembly, and threats to the health of freshwater systems from toxic algal blooms (Pecl et al. 2017).

IPCC concluded with *high confidence* that climate change will exacerbate the extinction risk for terrestrial and freshwater species over the 21st century (IPCC 2014b). A recent study suggests that local extinctions related to climate change are already widespread, with 47 percent of 976 species reviewed having experienced climate-related local extinctions (Wiens 2016). However, there is low agreement on the proportion of current species that are at risk from climate-related extinctions (ranging from 1 to 50 percent) (IPCC 2014b). For example, regional warming puts some bird populations at risk when increased predatory populations or declines in available habitat (resulting in fewer appropriate nesting and egg-laying spots) leads to increased vulnerability of their eggs to predators (Wormworth and Mallon 2010). Additionally, an increase in phosphorus and nitrogen in freshwater resources (eutrophication) from increased agricultural runoff is probable in the Northeast, California, and Mississippi Basin, especially in areas that experience heavier or more frequent precipitation events (GCRP 2014 citing Howarth et al. 2012, Howarth et al. 2006, Sobota et al. 2009, Justić et al. 2005, and McIsaac et al. 2002). The effects of eutrophication include excessive growth of algae (algal blooms), which reduce dissolved oxygen in the water, causing some plants, fish, and invertebrates to die.

Climate change may result in more uniform population structures, leading to increased competition and potentially resulting in extinctions (GCRP 2018a citing Ohlberger et al. 2014 and Lancaster et al. 2017). For example, extreme weather events can benefit invasive species by decreasing native communities' resistance and by occasionally putting native species at a competitive disadvantage (GCRP 2018a citing Diez et al. 2012, Kats et al. 2013, Tinsley et al. 2015, and Wolf et al. 2016).

[21] Referring to an organism's observable traits, such as color or size.

[22] Referring to an organism's genetic makeup.

[23] Referring to an organism's structural or anatomical features (e.g., egg size, wing shape, or even of the organism as a whole).

Diverse observations suggest that global terrestrial primary production increased over the latter 20th and early 21st centuries due to a combination of the fertilizing effect of increasing atmospheric CO2, nutrient additions from human activities, longer growing seasons, and forest regrowth (GCRP 2018a citing Campbell et al. 2017, Graven et al. 2013, Wenzel et al. 2016, Zhu et al. 2016, and Domke et al. 2018). Conversely, in areas experiencing extended drought (such as the western United States in 2014), water stress results in decreased tree growth (IPCC 2014b). A more intense hydrological cycle, including more frequent droughts, may reduce photosynthesis and therefore reduce ecosystem productivity and carbon storage (GCRP 2017). Alternatively, as plants gain more biomass, their net storage of carbon might be limited by nutrient availability in soils (Finzi et al. 2011). Within a few decades, it is possible that changes in temperature and precipitation patterns will exceed nitrogen and CO_2 as key drivers of ecosystem productivity (IPCC 2014b).

Elevated CO_2 concentrations have physiological impacts on plants, which can result in changes in both plant water utilization and local climate. A process referred to as CO_2-physiological forcing (Cao et al. 2010) occurs when increased CO_2 levels cause plant stomata (pores in plant leaves, which allow for gas exchange of CO_2 and water vapor) to open less widely, resulting in decreased plant transpiration (Cao et al. 2010). Reduced stomata opening increases water use efficiency in some plants, which can increase soil moisture content, thus mitigating drought conditions (McGrath and Lobel 2013 citing Ainsworth and Rogers 2007, Leakey 2009, Hunsaker et al. 2000, Conley et al. 2001, Leakey et al. 2004 and 2006, and Bernacchi et al. 2007). Reduced plant transpiration can also cause a decrease in evapotranspiration, which may trigger adjustments in water vapor, clouds, and surface radiative fluxes. These adjustments could ultimately drive macroclimatic changes in temperature and the water cycle (Cao et al. 2010). However, an observational study indicates minimal change in transpiration from increased CO_2 due to competing forces (Tor-ngern et al. 2014). Elevated CO_2 concentrations may also affect soil microbial growth rates and their impact on terrestrial carbon pools; however, these effects are complex and not well understood (Wieder et al. 2014; Bradford et al. 2016).

Ecological tipping points[24] begin with initial changes in a biological system (for example, the introduction of a new predatory animal species to the system due to changes in climate that are favorable to the newly introduced species), which are then amplified by positive feedback loops and can lead to cascading effects throughout the system. The point at which the system can no longer retain stability is a threshold known as a tipping point. Changes in such situations are often long- lasting and hard to roll back; managing these conditions is often very difficult (IPCC 2014b citing Leadley et al. 2010). Leadley et al. (2010) evaluated the potential tipping point mechanisms and their impacts on biodiversity and ecosystem services for several ecosystems. Examples include warming tundra that will reduce albedo, providing a warming feedback that will result in further thawing of tundra; and the large-scale changes in Amazonian rainforests to agricultural lands, resulting in decreased local and regional rains, promoting further decline of trees.

Forest ecosystems and services are at risk of greater fire disturbance when they are exposed to increased warming and drying, as well as declines in productivity and increases in insect disturbances (such as pine beetles). Boreal fire regimes have become more intense in terms of areas burned, length of fire season, and hotter, more energetic fires (IPCC 2014b citing Girardin and Mudelsee 2008, Macias and Johnson 2008, Kasischke et al. 2010, Turetsky et al. 2011, Mann et al. 2012, Girardin et al. 2013a). Cascading effects in forests are possible when fire-related changes in forest composition result in

[24] An ecological tipping point is described by IPCC (2014b), in reference to the potential for Amazonian ecosystem shifts, as "a large-scale, climate-driven, self-reinforcing transition" of one ecosystem into another type.

reduced capacity as a carbon sink and reduced albedo, both of which factor into further warming, putting forests at even greater risk of fire and dieback (IPCC 2014b citing Bond-Lamberty et al. 2007, Goetz et al. 2007, Welp et al. 2007, Euskirchen et al. 2009, Randerson et al. 2006, Jin et al. 2012, and O'Halloran et al. 2012).

Limiting warming to 2.7°F (1.5°C) compared to 3.6°F (2°C) may benefit terrestrial and wetland ecosystems through avoidance or reduction of changes, such as biome transformation, species range losses, and increased extinction risks (all *high confidence*) (IPCC 2018 citing Hoegh-Guldberg et al. 2018).

Adaptation

In the context of natural resource management, adaptation is about managing changes (GCRP 2014 citing Staudinger et al. 2012, Link et al. 2010, and West et al. 2009). The ability or inability of ecosystems to adapt to change is referred to as adaptive capacity. There could be notable regional differences in the adaptive capacity of ecosystems, and adaptive capacity is moderated by anthropogenic influences and capabilities. The ultimate impact of climate change on ecosystems depends on the speed and extent to which these systems can adapt to a changing climate. Rapid rather than gradual climate change may put populations at risk of extinction before beneficial genes are able to enhance the fitness of the population and its ability to adapt (Staudinger et al. 2013 citing Hoffmann and Sgro 2011).

Some adaptation strategies include habitat manipulation, conserving populations with more genetic diversity or behaviors, relocation (or assisted migration), and offsite conservation (such as seed banking and captive breeding) (GCRP 2014 citing Weeks et al. 2011, Peterson et al. 2011, Cross et al. 2013, and Schwartz et al. 2012). EPA (2016g) stresses the enhancement of natural buffers to protect and help ecosystems increase adaptive capacity. Anthropogenic stressors can compound climate change impacts, so reducing these effects, such as nutrient pollution or invasive species introduction, can bolster resilience (NPS 2016). The 2018 NCA report indicates the effectiveness of existing adaptation strategies and approaches may be significantly reduced in the face of a changing climate (GCRP 2018a).

Ocean Systems, Coasts, and Low-Lying Areas

This section provides an overview of recent findings regarding observed and projected impacts of climate change on ocean systems, coasts, and low-lying areas in the United States and globally. Ocean systems cover approximately 71 percent of the Earth's surface and include many habitats that are vital for coastal economies. Coastal systems and low-lying areas include all areas near the mean sea level. Coastal systems consist of both natural systems (i.e., rocky coasts, beaches, barriers, sand dunes, estuaries, lagoons, deltas, river mouths, wetlands, and coral reefs) and human systems (i.e., the built environment, institutions, and human activities) (IPCC 2014b).

In general, global ocean surface temperatures have risen at an average rate of 1.3°F ± 0.1°F (0.7°C ± 0.08°C) per century and have risen at a higher rate from 2000 to 2016 than from 1950 to 2016 (GCRP 2018a citing Jewett and Romanou 2017; Blunden and Arndt 2017). IPCC concludes that ocean temperatures are *very likely* to increase in the future, with impacts on climate, ocean circulation, chemistry, and ecosystems (IPCC 2013b). From 1971 to 2010, global oceans have absorbed 93 percent of all extra heat stored in earth's systems (UN 2016; Cheng et al. 2019). Ocean systems absorb approximately 25 percent of anthropogenic CO_2 emissions, leading to changes in ocean pH, which affects the formation of some marine species that are crucial to ocean health (GCRP 2014; UN 2016). The combination of warming and acidification across water bodies has adverse impacts on key habitats such as coral reefs and results in changes in distribution, abundance, and productivity of many marine species.

Observed and Projected Climate Impacts

Approximately 600 million people globally live in the Low Elevation Coastal Zone (IPCC 2014b citing McGranahan et al. 2007), with approximately 270 million people exposed to the 1-in-100-year extreme sea level (Jongman et al. 2012). Globally, there has been a net migration to coastal areas, largely in flood- and cyclone-prone regions, increasing the number of individuals at risk (IPCC 2014b citing de Sherbinin et al. 2011). Without adaptation, hundreds of millions of people may be displaced due to episodic localized flooding associated with storm surge and coastal flooding and land loss from sea-level rise by 2100, with the majority from eastern, southeastern, and southern Asia (Jongman et al. 2012; GCRP 2018a).

Even under the RCP2.6 low emissions scenario, the frequency, depth, and extent of high tide and more-severe and damaging coastal flooding in the United States are projected to increase rapidly over the coming decades (GCRP 2018a). In the United States, 133.2 million people live in coastal zone counties (GCRP 2018a citing Kildow et al. 2016), and analysis indicates that 4.2 million Americans could be at risk under a scenario of 3 feet of sea-level rise, and 13.1 million people under 6 feet of sea-level rise, which could drive mass migration and societal disruption (Hauer 2017; Hauer et al. 2016).[25] New high-resolution digital elevation models improve estimates of potential future population exposure to sea-level rise. For example, assuming sea-level rise projections under RCP8.5, these new models reveal that up to 630 million people live on land that could be exposed to annual coastal flood levels in 2100 (Kulp and Strauss 2019). Such increases in sea-level rise and annual flooding present dramatic risks to coastal communities. Those at risk include a substantial number of individuals in a high social vulnerability category, with less economic or social mobility and who are less likely to be insured (GCRP 2014).

Coastal inundation and flooding are the product of both long-term sea-level rise and dynamic short-term processes such as storm surge, erosion, and ocean tides (GCRP 2018a; Barnard et al. 2019). Climate change is expected to exacerbate all of these coastal processes, potentially altering coastal life and disrupting coast-dependent economic drivers and activities and services, some of which—such as transportation and energy infrastructure, and water resources—are particularly sensitive to these changes. (GCRP 2014; IPCC 2014b citing Handmer et al. 2012, Horton et al. 2010, Hanson and Nicholls 2012, and Aerts et al. 2013). Increased sea surface temperature and ocean heat content are projected to facilitate additional tropical storm activity and increase the probability of high rainfall tropical cyclones (Trenberth et al. 2018; Emanuel 2017). In turn, extreme storms can erode or remove sand dunes and other land elevations, exposing them to inundation and further change (GCRP 2014). Rising water temperatures and other climate-driven changes (e.g., salinity, acidification, and altered river flows) will affect the survival, reproduction, and health of coastal plants and animals (GCRP 2014; UN 2016). Shifts in the distribution of species and ranges, changes in species interactions, and reduced biodiversity cause fundamental changes in ecosystems and can adversely affect economic activities such as fishing (GCRP 2014). For instance, major marine heat wave events along the Northeast Coast of the United States in 2012 and the entire West Coast in 2014 through 2016 caused ocean temperatures to increase greater than 2°C above the normal range, a level similar to average conditions expected later this century under

[25] The NOAA Sea Level Rise visualization tool shows inundation footprints associated with different sea-level rise simulations along the continental U.S. coast (NOAA, Office for Coastal Management, DigitalCoast, Sea Level Rise Viewer, https://coast.noaa.gov/digitalcoast/tools/slr.html). This and other tools can be used to understand and assess risks from sea-level rise.

future climate scenarios (GCRP 2017). These events caused changes in the coastal ecosystems, including the appearance of warm-water species, increased mortality of marine mammals, and an unprecedented harmful algal bloom, all of which contributed to economic stress for the fisheries in these regions.

Species with narrow physiological tolerance to change, low genetic diversity, specific resource requirements, or weak competitive abilities will be particularly vulnerable to climate change (GCRP 2014 citing Dawson et al. 2011 and Feder 2010). For example, during the end-Permian mass extinction, a change in ocean pH of approximately 0.3, which is consistent with current projections for pH changes over the next 100 years, resulted in a loss of approximately 90 percent of known species (NRC 2013b). Under the RCP8.5 scenario, the Atlantic, Pacific, and Indian Oceans are projected to see a 15 to 30 percent decrease in total marine animal biomass by 2100. Meanwhile, polar oceans are projected to see a 20 to 80 percent decrease (Bryndum-Buchholz et al. 2018). Overall, projected shifts in fish and species distribution and decreases in their population due to climate change pose risks to income, food security and livelihoods of marine-based communities (IPCC 2019a).

Studies indicate that 75 percent of the world's coral reefs are threatened due to climate change and localized stressors (GCRP 2014 citing Burke et al. 2011, Dudgeon et al. 2010, Hoegh-Guldberg et al. 2007, Frieler et al. 2013, and Hughes et al. 2010). There are already 25 coral species listed under the Endangered Species Act (NOAA 2021). Further, IPCC projects that when average global warming reaches 1.3°C above pre-industrial levels, tropical coral reefs are *virtually certain* to experience high risks of impacts, such as frequent mass mortalities, and at 2°C, most available evidence (*high agreement, robust evidence*) suggests that coral-dominated ecosystems will be nonexistent (IPCC 2013a citing Alvarez-Filip et al. 2009). The potential for coastal ecosystems to pass a tipping point threshold is of particular concern, as these changes can be irreversible (GCRP 2014 citing Hoegh-Guldberg et al. 2007 and Hoegh-Guldberg and Bruno 2010).

Several studies have analyzed the impact of climate change on historical and future coral bleaching. According to an analysis of bleaching records at 100 globally distributed reef locations from 1980 to 2016, the time between recurrent severe coral bleaching events has decreased steadily to 6 years during this period, and coral bleaching is occurring more frequently in all El-Niño-Southern Oscillation phases. These trends prevent the full recovery of mature coral assemblages between bleaching events (Hughes et al. 2018). Based on the high emissions scenario (RCP8.5), by 2055, 90 percent of reef locations are projected to experience annual severe bleaching events, and by 2034, all reef locations are projected to experience 5 percent declines in calcification. In general, the projected year of onset for annual severe bleaching events varies based on latitude, with reefs at lower latitudes expected to experience these events earlier than those at higher latitudes (van Hooidonk et al. 2014; Sully et al. 2019).

NOAA concluded that there is *very high confidence* that global average sea level has risen by 0.16 to 0.21 meters since 1900, with a 0.07-meter rise occurring since 1993 (Sweet et al. 2017b). GCRP notes that it is *very likely* that global average sea level will rise by 0.09 to 0.18 meter by 2030, 0.15 to 0.38 meter by 2050, and 0.3 to 1.2 meters by 2100, relative to 2000 (Sweet et al. 2017b). NOAA extends the upper limits of these estimates to a rise of 0.16 to 0.63 meter by 2050 and a rise of 0.3 to 2.5 meters by 2100 (Sweet et al. 2017a). GCRP concluded it is *extremely likely* that temperature increases account for 59 percent of the rise in global sea level during the 20th century (GCRP 2017 citing Kopp et al. 2016). The change in sea level is attributed to thermal expansion of ocean water, thawing of permafrost, and mass loss from mountain glaciers, ice caps, and ice sheets. Sea-level rise was found to be non-uniform around the world, which might result from variations in thermal expansion; exchanges of water, ocean, and atmospheric circulation; and geologic processes (IPCC 2014b; UN 2016). Higher sea levels cause greater coastal erosion; changes in sediment transport and tidal flows; landward migration of barrier shorelines; fragmentation of islands; and saltwater intrusion into aquifers, croplands, and estuaries (GCRP 2014 citing Burkett and Davidson 2012, CCSP 2009, IPCC 2007a, Irish et al. 2010, Rotzoll and Fletcher 2013; Nicholls and Cazenave 2010). Higher sea levels also result in the loss of coastal wetland environments; it was estimated that the United States lost an average of about 80,160 acres of U.S. coastal wetland environments per year between 2004 and 2009 (GCRP 2018a citing Dahl and Stedman 2013). At this rate, the United States would lose an additional 16 percent of coastal wetlands by 2100. Sea-level rise will expand floodplain areas and place more individuals in high-hazard zones; coastal communities could face increased flooding and erosion. Coastal systems and low-lying areas are expected to experience more submergence, flooding, and erosion of beaches, sand dunes, and cliffs (IPCC 2014b).

Oceans have absorbed approximately 28 percent of the human-caused CO_2 over the last 250 years, resulting in a decrease in pH of 0.11 unit[26] since preindustrial times and an expected further decrease of from 0.3 to 0.4 unit by 2100 (Feely et al. 2009; GCRP 2014 citing NRC 2010, Sabine et al. 2004, and Feely et al. 2009; Longo and Clark 2016 citing Guinotte and Fabry 2008; EPA 2016h). IPCC concluded there is *very high confidence* that coastal areas experience considerable temporal and spatial variability in seawater pH compared to the open ocean due to additional natural and human influences (IPCC 2014b). Increased CO_2 uptake in the oceans makes it more difficult for organisms to form and maintain calcium carbonate shells and skeletal structures; increases erosion and bleaching of coral reefs and their biodiversity; and reduces growth and survival of shellfish stocks globally (GCRP 2014 citing Tribollet et al. 2009, Wisshak et al. 2012, and Doney et al. 2009; Hönisch et al. 2010; Lemasson et al. 2017). For instance, the GCRP notes that under the high emissions scenario (RCP8.5), by 2100, nearly all coral reefs are projected to be surrounded by acidified seawater that will challenge coral growth (GCRP 2018a citing Ricke et al. 2013). IPCC concluded there is *high confidence* that coastal acidification will continue into the 21st century but with large, uncertain regional variation (IPCC 2014b). Further, the GCRP notes that under the RCP8.5 emissions scenario, by 2050, 86 percent of ecosystems will experience combinations of temperature and pH that have never before been experienced by modern species (GCRP 2018a citing Henson et al. 2017).

Hypoxia in ocean environments is a condition under which the dissolved oxygen level in the water is low enough to be detrimental to resident aquatic species. Oxygen solubility decreases as temperatures increase, with greater sensitivity at lower temperatures. As a result, warming sea surface temperatures will decrease oxygen concentrations in the ocean, especially at high latitudes where predicted rates of warming are higher. In addition, warmer sea surface temperatures enhance stratification, which prevents oxygen-rich surface water from mixing with deeper water where hypoxia typically occurs. Stratification can also be a result of sea-level rise, which increases the overall volume of shallow coastal water that is susceptible to hypoxia (Altieri and Gedan 2015). Global ocean oxygen content has decreased by more than 2 percent since 1960, with large variations in oxygen loss across ocean basins and depths (Schmidtko et al. 2017). Global oxygen content in the upper ocean (0 to 1,000 meters) is also estimated to have changed at the rate of $-243 \pm 124\ 10^{12}$ mol oxygen per decade between 1958 and 2015 (Ito et al. 2017). Accordingly, oxygen-minimum zones have been growing and are projected to continue expanding to temperate and subpolar regions with future warming (IPCC 2014b). Models project that oxygen levels in the oceans will continue to decline through 2100 by 2.4 to 3.5 percent under the RCP4.5 and RCP8.5 emissions scenarios, respectively, with greater losses regionally and in deep sea areas (Jewett and Romanou 2017 citing Bopp et al. 2013). Decreased oxygen concentrations and hypoxia affect the physiology, behavior, and ecology of marine organisms. For instance, hypoxia has

[26] The pH scale is logarithmic; therefore, each whole unit decrease in pH is equivalent to a 10-fold increase in acidity.

the potential to affect the visual behavior of organisms as visual tissues have high oxygen demands (McCormick and Levin 2017). Hypoxia may also cause deterioration in the reproductive systems of both male and female fish, leading to a significant decrease in hatching success (Lai et al. 2019). The ability of marine organisms to survive in hypoxic conditions is further strained by warming ocean temperatures. Marine benthic organisms (i.e., organisms that live on or near the ocean floor) have been shown to have significantly shortened survival times when subjected to warmer hypoxic conditions (Vaquer-Sunyer and Duarte 2011).

Ocean salinity levels can be affected by freshwater additions, ocean evaporation, and the freezing or thawing of ice caps and glaciers. Marine organisms are adapted to specific levels of ocean salinity and often become stressed by changing salinity levels. Additionally, changing ocean salinity levels affect the density of water, which in turn affects factors such as the availability of local drinking water and, potentially, global ocean circulation patterns. Although the globally averaged salinity change is small, changes in regional basins have been significant. Salinity in ocean waters has decreased in some tropical and higher latitudes due to a higher precipitation-to-evaporation ratio and sea-ice melt (IPCC 2014b citing Durack et al. 2012). Evaporation-dominated subtropical regions are exhibiting definite salinity increases, while regions dominated by precipitation are undergoing increasing freshening in response to intensification of the hydrological cycle. These effects are amplified in regions that are experiencing increasing precipitation or evaporation. Findings through surface water analyses of the Atlantic Ocean show increased salinity, while the Pacific Ocean demonstrates decreased salinity, and the Indian Ocean has observed minimal changes (Durack and Wijffels 2010).

Net primary production refers to the net flux of carbon from the atmosphere into organic matter over a given period.[27] Ocean systems provide approximately half of global net primary production. Net primary production is influenced by physical and chemical gradients at the water surface, light, and nutrient availability. A changing climate alters the mixed layer depth, cloudiness, and sea-ice extent, thus altering net primary production. Open-ocean net primary production is projected to reduce globally, with the magnitude of the reduction varying depending on the projection scenario (IPCC 2014b). Impacts on primary productivity vary significantly across regions. While primary productivity in the tropics and temperate zones is projected to decrease, primary productivity in high-latitude regions, particularly the Arctic, showed positive trends from 2003 to 2016 in all but one of nine regions, with statistically significant trends occurring in five regions (NOAA 2016).

Adaptation

The primary adaptation options for sea-level rise are retreat, accommodation, and protection (IPCC 2014b citing Nicholls et al. 2011), which are all widely used around the world (IPCC 2014b citing Boateng 2010 and Linham and Nicholls 2010). Retreat allows the impacts of sea-level rise to occur unobstructed as inhabitants pull back from inundated coastlines. Accommodation is achieved by increasing the flexibility of infrastructure and adjusting the use of at-risk coastal zones (IPCC 2014b). Protection is the creation of barriers against sea intrusion with replenished beaches and seawalls. Ecosystem-based protection strategies, which include the protection and restoration of relevant coastal natural systems (IPCC 2014b citing Schmitt et al. 2013), oyster reefs (IPCC 2014b citing Beck et al. 2011), and salt marshes (IPCC 2014b citing Barbier et al. 2011) are increasingly attracting attention (IPCC 2014b citing Munroe et al. 2011). In addition, reducing nonclimate stresses (e.g., coastal pollution, overfishing,

[27] Net primary production is estimated as the amount of carbon synthesized via photosynthesis minus the amount of carbon lost via cellular respiration.

development) may increase the climate resilience of framework organisms (i.e., tropical corals, mangroves, and seagrass) (World Bank 2013; Ellison 2014; Anthony et al. 2015; Sierra-Correa and Cantera Kintz 2015; Kroon et al. 2016; O'Leary et al. 2017; Donner 2009).

Advances have been made in the United States in the past few years in terms of coastal adaptation, science, and practice, but most coastal managers are still building their capacities for adaptation (GCRP 2014 citing NRC 2010, Carrier et al. 2012, Moser 2009, and Poulter et al. 2009). Some examples of coastal adaptation include integrating natural landscape features with built infrastructure (green and gray infrastructure[28]) to reduce stormwater runoff and wave attack, constructing seawalls around wastewater treatment plants and pump stations, pumping effluent to higher elevations as sea levels rise, pumping freshwater into coastal aquifers to mitigate salt water infiltration, developing flood-proof infrastructure, relocation of coastal infrastructure away from the coast, and relocation of communities away from high-hazard areas (GCRP 2014). Some examples of ocean adaptation include reducing overfishing, establishing protected areas, and conserving habitat to increase resilience; culturing acid-resistant strains of shellfish; oyster reef and mangrove restoration; coral reef restoration and protection; and developing alternative livelihood options for marine food-producing sectors (GCRP 2014).

Food, Fiber, and Forest Products

Increases in atmospheric CO_2, combined with rising temperatures and altered precipitation patterns, have begun to affect both agricultural and forest systems (Walthall et al. 2013; GCRP 2014; IPCC 2014d; USDA 2015; USFS 2016; FAO 2015; GCRP 2015). These impacts are expected to become more severe and to affect food security (FAO 2015; GCRP 2015).

Observed and Projected Climate Impacts

Climate disruptions to agricultural production have increased over the past 40 years and are projected to further increase over the next 25 years. Crop and livestock production projections indicate that climate change effects through 2030 will be mixed (IPCC 2014b; Walthall et al. 2013); however, most predictions for climate change impacts on crop yields by 2050 are negative (Nelson et al. 2014; IPCC 2014b; Müller and Robertson 2014). Currently, yields for some crops are increasing; however, climate change could be diminishing the rate of these increases, inducing a 2.5 percent decrease in yield growth rates per decade (GCRP 2015 citing Porter et al. 2014). Generally, yields and food security are at greater risk in poor, low-latitude countries (FAO 2015; GCRP 2015).

Specific climate impacts on agriculture will vary based on the species, location, timing, and current productivity of agricultural systems (including crops, livestock, and fish) at local, national, and global scales (GCRP 2014; USDA 2015). Bench- and field-scale experiments have found that over a certain range of concentrations, greater CO_2 levels have a fertilizing impact on plant growth (e.g., Long et al. 2006; Schimel et al. 2000) with considerable variability among regions and species (McGrath and Lobell 2013). However, climate change is projected to cause multiple abiotic (nonliving) stressors (such as temperature, moisture, extreme weather events), and biotic (living) stressors (such as disease, pathogens, weeds and insects) on crop production (Thornton et al. 2014; IPCC 2014b; GCRP 2017, 2018a). Increased frequency and intensity of extreme weather events (including extreme heat, precipitation, and storm events) is expected to negatively influence crop, livestock, and forest

[28] Green infrastructure refers to sustainable pollution reducing practices that also provide other ecosystem services (e.g., permeable pavements, green roofs). Gray infrastructure refers to traditional practices for stormwater management and wastewater treatment, such as pipes and sewers.

productivity and increase the vulnerability of agriculture and forests to climate risks (Walthall et al. 2013; GCRP 2014, 2018a; IPCC 2014b; USDA 2015; EPA 2016h; USFS 2016; Vogel et al. 2019b). Additionally, climate change is projected to affect a wide range of ecosystem processes, including maintenance of soil quality and regulation of water quality and quantity (GCRP 2014, 2018a; USDA 2015). Changes in these and other ecosystem services will exacerbate stresses on crops, livestock, and forests (Walthall et al. 2013; GCRP 2014, 2018a). Major staple crops (wheat, rice, maize, and soybean) could suffer reduced yields between 3 and 7.4 percent for each degree-Celsius increase in global mean temperature (Zhao et al. 2017). Livestock are vulnerable as climate change is affecting the nutritional quality of pastures and grazing lands; affecting the production, availability, and price of feed-grains; stressing animals; hurting overall animal wellbeing (i.e., animal health, growth, and reproduction and distribution of animal diseases and pests); and decreasing livestock productivity (e.g., meat, milk, and egg production) (IPCC 2014b; IPCC 2014b citing André et al. 2011, Renaudeau et al. 2011; GCRP 2015; GCRP 2014 citing Rötter and Van de Geijn 1999, Nardone et al. 2010, Walthall et al. 2013, and West 2003; GCRP 2018a citing Key et al. 2014, Amundson et al. 2006, Dash et al. 2016, Rojas-Downing et al. 2017, Giridhar and Samireddypalle 2015, Lee et al. 2017, Paul et al. 2007, and Zhorov 2013). Overall, climate change is predicted to negatively affect livestock on almost all continents (IPCC 2014b). Climate change impacts on agriculture may also affect socioeconomic conditions, such as the amount of crop insurance paid to cover losses from extreme climate conditions (Walsh et al. 2020).

Studies have concluded that climate change is affecting aquatic ecosystems, including marine and freshwater fisheries (IPCC 2014b; Groffman et al. 2014). Climate change impacts on marine fisheries have primarily been linked to increasing temperatures (including both mean and extreme temperatures) but are also affected by increasing CO_2 concentrations and ocean acidification (IPCC 2014b; GCRP 2018a). Fisheries are affected by increases in ocean temperatures, resulting in many marine fish species migrating to deeper or colder water, additional stress to already-strained coral reefs, and an expansion in warm freshwater habitats and a shrinkage of cool- and cold freshwater habitats (IPCC 2014b; NOAA 2015a). The Food and Agriculture Organization of the United Nations estimates that by 2050, the average total marine maximum catch potential in the world's Exclusive Economic Zones could decline by 7 to 12 percent (relative to 2000) under a higher emissions scenario (RCP8.5); by 2100, this decrease could be as much as 16 to 25 percent (Bell and Bahri 2018 citing FAO 2018). However, these decreases would not be consistent around the globe. Another study found that fisheries productivity could experience a decline in maximum catch potential of 10 to 47 percent as compared to the 1950–1969 level under RCP8.5 in the contiguous United States and increase in potential of 10 percent in the Gulf of Alaska and 46 percent in the Bering Sea (GCRP 2018a citing Cheung et al. 2016).

Climate change threatens forests by increasing tree mortality and forest ecosystem vulnerability due to fire, insect infestations, drought, disease outbreaks, increasing temperatures, and extreme weather events (Joyce et al. 2014; IPCC 2014b; USFS 2016; GCRP 2018a; Aleixo et al. 2019; Williams et al. 2019). Currently, tree mortality is increasing globally due in part to high temperatures and drought (IPCC 2014b). IPCC concludes there is *medium confidence* that this increased mortality and forest dieback (high mortality rates at a regional scale) will continue in many regions around the globe through 2100 (IPCC 2014b). However, due to the lack of models and limited long-term studies, projections of global tree mortality are currently highly uncertain (IPCC 2014b citing McDowell et al. 2011). GCRP estimates that water-limited forests will be further constrained by a warmer climate, while energy-limited forests may experience an increase in growth due to climate change (GCRP 2018a).

Other climate change induced direct and indirect effects, such as changes in the distribution and abundance of insects and pathogens, fire, changes in precipitation patterns, invasive species, and extreme weather events (e.g., high winds, ice storms, hurricanes, and landslides) are also affecting forests (GCRP 2017; Thornton et al. 2014; IPCC 2014b; GCRP 2014; IPCC 2014b citing Allen et al. 2010a). A dramatic increase in the area burned by wildfire and risk of wildfire is projected in the contiguous United States through 2100, especially in the West (EPA 2015c; Halofsky et al. 2017; Tett et al. 2018). Tree species are predicted to shift their geographic distributions to track future climate change (Zhu et al. 2014; USFS 2016).

IPCC concludes that while there is currently *high confidence* that forests are serving as a net carbon sink globally, it is unclear if this trend will continue (IPCC 2014b). GCRP expects carbon storage to generally decrease in the future due to increased temperatures, more frequent droughts, and increased disturbances (GCRP 2018a). In recent years, the rate of sequestration of excess carbon by intact and newly growing forests appears to have stabilized (IPCC 2014b citing Canadell et al. 2007 and Pan et al. 2011). Warming, changes in precipitation, pest outbreaks, and current social trends in land use and forest management are projected to affect the rate of CO_2 uptake in the future (Joyce et al. 2014; IPCC 2014b citing Allen et al. 2010a), making it difficult to predict whether forests will continue to serve as net carbon sinks in the long term (IPCC 2014b). In addition, historic land uses have a legacy effect on patterns of carbon uptake in forests, further complicating the calculation of future CO_2 sequestration patterns (Thom et al. 2018).

Climate change impacts on food security and food systems are predicted to be widespread, complex, geographically and temporally variable, and greatly influenced by socioeconomic conditions (IPCC 2014b citing Vermeulen et al. 2012). For example, smallholder farmers—a group that suffers from chronic food insecurity—are especially vulnerable to the risks of pests, diseases, and extreme weather events that are made worse by climate change (Mbow et al. 2019). An additional challenge for food security will be future population growth, with global population projected to reach 9.8 billion by 2050 (GCRP 2018a citing Hallström et al. 2015, Harwatt et al. 2017, U.N. Department of Economic and Social Affairs 2017). Food security comprises four key components: production; processing, packaging, and storage; transportation; and utilization and waste (GCRP 2014 citing FAO 2011), all of which are closely tied to poverty (IPCC 2014b). Projected rising temperatures, changing weather patterns, and increases in the frequency of extreme weather events will affect food security by potentially altering agricultural yields, post-harvest processing, food and crop storage, transportation, retailing, and food prices (GCRP 2014). Many of these impacts are expected to be negative, including decreasing production yields; harming pollinators; increasing costs and spoiling during processing, packaging, and storage; inhibiting water, rail, and road transportation; and increasing food safety risks (GCRP 2015; Giannini et al. 2017). The negative consequences of climate change—decreased crop yields, nutrition, and food security—are projected to be more severe under 2°C of warming than under 1.5°C of warming (*high confidence)* (IPCC 2018).

Currently, the vast majority of undernourished people live in developing countries (IPCC 2014b). Both due to the nature of the direct impacts and the means to implement adaptation strategies, climate change poses the greatest food security risks to poor and tropical region populations, and the least risk to wealthy, temperate, and high-latitude region populations (GCRP 2015; FAO 2015). As most countries import at least some of their domestic food consumed, climate change has the potential to affect not just food production but also the amount of food countries import and export. Import demand is expected to increase for developing nations lacking advanced technologies and practices and producing low agricultural yields (GCRP 2015).

Adaptation

Over the past 150 years, the agricultural and forestry sectors have demonstrated an impressive capacity to adapt to a diversity of growing conditions amid dynamic social and economic changes (Walthall et al. 2013; Joyce et al. 2014; FAO 2015; GCRP 2015). Recent changes in climate, however, threaten to outpace the current adaptation rate and create challenges for the agricultural sector and associated socioeconomic systems (GCRP 2014; IPCC 2014b). Economic literature indicates that in the short term, producers will continue current adaptation practices for weather changes and shocks (e.g., by changing timing of field operations, shifts in crops grown, changing tillage/irrigation practices) (GCRP 2014 citing Antle et al. 2004). In the long term, however, current adaptation technologies are not expected to buffer the impacts of climate change sufficiently (GCRP 2014, 2018a). In fact, significant shifts in crop choice and land-use patterns will be required in order to sustain production growth and match global demand (Mbow et al. 2019).

To minimize these impacts, a variety of resilience actions can be implemented, including management and policy, engineering, and insurance responses. Management practices associated with sustainable agriculture, such as diversifying crop rotations and crop varieties, integrating livestock with crop production systems, improving soil quality, and minimizing off-farm flows of nutrients and pesticides can increase resiliency to climate change (GCRP 2014 citing Easterling 2010, Lin 2011, Tomich et al. 2011, and Wall and Smit 2005; Li et al. 2019). Furthermore, the use of heat- and stress-tolerant and other adaptively advantageous varieties of crops can aid in yield increases in the face of climate change (Zhang and Zhao 2017; GCRP 2018a). Enhancing genetic resources via genetic modification and improved breeding systems also has great potential to enhance crop resilience (GCRP 2015 citing Jacobsen et al. 2013 and Lin 2011).

For livestock, adaptive capacity is limited by high costs and competition. Possible adaptation measures include breeding livestock to genetically adapt to local conditions, improving the design of livestock housing, and implementing management strategies that cool livestock and reduce stress (GCRP 2018a). However, cooling strategies are not always economically feasible due to high infrastructure and energy demands (GCRP 2015). Furthermore, increased shade and moisture can heighten pathogen risk (Fox et al. 2015). Irrigation strategies to improve feed quality and quantity could also be limited by competition with other water users, especially in arid climates (GCRP 2015 citing Elliott et al. 2014). To enhance resilience against increased pathogen risk, adaptation strategies include no-regrets strategies, disease surveillance and response, disease forecast capacity, animal health service delivery, eradication of priority diseases, increased diversification and integration of livestock with agriculture, breeding resilient animals, and monitoring impacts of land-use change on disease (Grace et al. 2015). Fisheries have developed a number of adaptation practices as well. For example, NOAA's Climate Science Strategy (2015b) sets forth the objective of designing adaptive decision processes to enable fisheries to enhance fishery resilience.

Forest management responses to climate change will be influenced by the changing nature of private forestland ownership, globalization of forestry markets, emerging markets for bioenergy, and climate change policy (Walthall et al. 2013; Joyce et al. 2014). The emerging market for bioenergy—the use of plant-based material to produce energy—has the potential to aid in forest restoration (Joyce et al. 2014). At the same time, possible projected declines in a skilled forest sector workforce and timber product output (and lower prices for timber) could pose a challenge to climate change adaptation of forests (GCRP 2018a citing U.S. Forest Service 2016). Flexible policies that are not encumbered with legally binding regulatory requirements can facilitate adaptive management where plants, animals, ecosystems, and people are responding to climate change (Joyce et al. 2014 citing Millar and Swanston 2012). Ultimately, maintaining a diversity of tree species could become increasingly important to maintain the adaptive capacity of forests (Duveneck et al. 2014). Carbon sequestration losses can be mitigated using sustainable land-management practices (GCRP 2015 citing Branca et al. 2013).

In terms of food security, global undernourishment dropped from 19 percent in 1990 through 1992 to 11 percent in 2014 (GCRP 2015). However, it is questionable whether this progress will continue given challenges posed by climate change (GCRP 2015). Developing and implementing new agricultural methods in low-yield regions, reducing waste in the food system, making food distribution systems more resilient to climate risks, protecting food quality and safety at higher temperatures, and policies to ensure food access for disadvantaged populations during extreme events are all adaptation strategies to mitigate the effects of climate change (GCRP 2014 citing Walthall et al. 2013, Ericksen et al. 2009, Misselhorn et al. 2012, Godfray et al. 2010, and FAO 2011; GCRP 2015). Ultimately, adaptation will become more difficult as physiological limits of plants and animal species are exceeded more frequently and the productivity of crop and livestock systems becomes more variable (GCRP 2014).

Urban Areas

This section defines urban areas and describes the existing conditions and their potential vulnerability to climate change impacts. Urban centers are now home to more than half of the global population, and this percentage continues to increase every year (IPCC 2014b citing UN DESA Population Division 2013 and World Bank 2008). In the United States, approximately 85 percent of the population lives in metropolitan areas[29] (GCRP 2018a). In addition to large numbers of people, urban centers also contain a great concentration of the world's economic activity, infrastructure, and assets (IPCC 2014b citing UN DESA Population Division 2013 and World Bank 2008; GCRP 2018a). However, definitions of urban centers and their boundaries vary greatly between countries and between various pieces of academic literature (IPCC 2014b).

Wealthy nations are predominantly urbanized, and low- and middle-income nations are rapidly urbanizing. The rate of urbanization is outstripping the rate of investment in basic infrastructure and services, which is creating urban communities with high vulnerability to climate change (IPCC 2014b citing Mitlin and Satterwaite 2013). Across urban communities, there are very large differences in the extent to which economies are dependent on climate-sensitive resources, but in general, a high proportion of people most at risk of extreme weather events are located in urban areas (IPCC 2014b citing IFRC 2010, UNISDR 2009, and UNISDR 2011).

Observed and Projected Climate Impacts

The risks of climate change to urban communities and their populations' health, livelihood, and belongings are increasing. Such risks include rising sea levels, storm surges, extreme temperatures, extreme precipitation events leading to inland and coastal flooding and landslides, drought leading to increased aridity and water scarcity, and various combinations of stressors exacerbating air pollution (IPCC 2014b). It cannot be assumed that climate change impacts will be the same or even similar in different cities (Silver et al. 2013). In addition, certain population groups may be more directly affected by climate change than other groups. For example, the very young and elderly are both more sensitive

[29] Metropolitan areas include urbanized areas of 50,000 or more population, plus adjacent territory that has a high degree of social and economic integration (Office of Management and Budget 2009).

to heat stress, some communities of color and tribal and Indigenous communities are disproportionately exposed to health risks related to climate hazards, those with preexisting health issues could be more sensitive to a range of stressors, and low-income groups and women could be more sensitive due to a lack of resources and discrimination in access to support services (Ebi et al. 2018; IPCC 2014b; Cutter et al. 2014; GCRP 2014 citing Bates and Swan 2007, NRC 2006, and Phillips et al. 2009). In turn, some populations most vulnerable to climate-related health hazards also experience greater challenges in accessing information, resources, and tools for building resilience to climate change (Ebi et al. 2018).

Cities that are projected to experience rising temperatures are apt to experience temperatures even higher than projected due to the urban heat island effect (whereby the volume of paved land in urban areas absorbs and holds heat along with other causes) (GCRP 2018a citing Hibbard et al. 2017; IPCC 2014b, 2019b). This could lead to increased health impacts, air pollution, and energy demand, disproportionately affecting low-income, young, historically underserved, and elderly populations (IPCC 2014b citing Hajat et al. 2010, Blake et al. 2011, Basagaña 2019, Campbell-Lendrum and Corvalan 2007, and Lemonsu et al. 2013, Akbari et al. 2016; Hoffman et al. 2020). Urbanization, through increased impermeable surfaces and microclimatic changes, can also increase flooding. Climatic trends, such as increased frequency of extreme precipitation and sea-level rise, will stress existing flood infrastructure (GCRP 2017; National Academies of Sciences, Engineering, and Medicine 2019).

Drought and reduced snowpack will have many effects in urban areas, including water shortages, electricity shortages (from decreased hydropower operation), water-related diseases (which could be transmitted through contaminated water), and food insecurity. Changes in precipitation due to climate change could create water demand conflicts between residential, commercial, agricultural, and infrastructure use (IPCC 2014b citing Roy et al. 2012 and Tidwell et al. 2012). Sea-level rise will result in "saline ingress, constraints in water availability and quality, and heightened uncertainty in long-term planning and investment in water and waste water systems" (IPCC 2014b citing Fane and Turner 2010, Major et al. 2011, and Muller 2007). Additionally, urban populations could be affected by "reductions in groundwater and aquifer quality..., subsidence, and increased salinity intrusion" (IPCC 2014b). Increased eutrophication from warming water temperatures will incur costs related to the upgrading of municipal drinking water treatment facilities and purchase of bottled water. Additionally, sea-level rise poses an additional risk to water treatment facilities (Baron et al. 2013).

In developed and developing countries, stormwater systems will be increasingly overwhelmed by extreme short-duration precipitation events if they are not upgraded (IPCC 2014b citing Howard et al. 2010, Mitlin and Satterthwaite 2013, and Wong and Brown 2009). If storm drains for transportation assets are blocked, then localized flooding can cause delays (GCRP 2014).

Climate change will have direct impacts on both the production and the demand side of the energy system. For example, individual or combinations of hazards may increase risk of direct physical damage to generation as well as transmission and distribution systems, reduce the efficiency of water cooling for large thermoelectric electricity generating facilities, reduce water availability for hydroelectric and wind power potential, and change demands for heating and cooling in developed countries (GCRP 2014; IPCC 2014b citing Mideksa and Kallbekken 2010, DOE 2015a; National Academies of Sciences, Engineering, and Medicine 2017a). Many power supply facilities such as power plants, refineries, pipelines, transmission lines, substations, and distribution networks are located in coastal environments and are thus subject to direct physical damage and permanent and temporary flooding from sea-level rise, higher storm surge and tidal action, increased coastal erosion, and increasingly frequent and intense storms and hurricanes (GCRP 2014; DOE 2015a citing CIG 2013 and GCRP 2014). They may also be negatively affected by the vulnerability of transportation systems that provide feedstocks such as coal (EIA 2017e; DOE 2015a citing DOE 2013c; Ingram et al. 2013).

Climate change impacts that decrease the reliability of or cause disruptions to the energy supply network could have far-reaching consequences on businesses, infrastructure, healthcare, emergency services, residents, water treatment systems, traffic management, and rail shipping (GCRP 2018a; IPCC 2014b citing Finland Safety Investigations Authority 2011, Halsnæs and Garg 2011, Hammer et al. 2011, and Jollands et al. 2007). Oil and gas availability for transportation in the United States would also be affected by increased energy demand in global markets as well as by climate change events. For example, DOE (2015a) concluded that 9 percent of U.S. refining capacity could be exposed to sea-level rise and storm surge in 2050 (assuming 23 inches of sea-level rise and a Category 3 storm), and strategic petroleum reserves may be exposed to flooding during lower-intensity storms.

The daily and seasonal operation of most transportation systems is already sensitive to fluctuations in precipitation, temperature, winds, visibility, and for coastal cities, rising sea levels (GCRP 2014 citing Ball et al. 2010, Markolf et al. 2019, Cambridge Systematics Inc. and Texas Transportation Institute 2005, and Schrank et al. 2011; IPCC 2014b citing Love et al. 2010). With climate change, the reliability and capacity of the transportation network could be diminished from an increased frequency of flooding and heat events and an increased intensity of tropical storms (GCRP 2014 citing NRC 2008; DOT 2019a). Telecommunication systems are also sensitive to flooding of electrical support systems, wind damages to cellular phone towers, corrosion due to flooding and sea-level rise, and unstable foundations due to permafrost melt (IPCC 2014b citing Zimmerman and Farris 2010 and Larsen et al. 2008).

Housing in urban areas is one of the pieces of infrastructure most heavily affected by extreme weather events such as cyclones and floods (IPCC 2014b citing Jacobs and Williams 2011). Housing that is constructed out of informal building materials (usually occupied by low-income residents) and without strict building codes is particularly vulnerable to extreme events (IPCC 2014b citing UNISDR 2011). Increased weather variability, including warmer temperatures, changing precipitation patterns, and increased humidity, accelerates the deterioration of common housing building materials (IPCC 2014b citing Bonazza et al. 2009, Grossi et al. 2007, Smith et al. 2008, Stewart et al. 2011, and Thornbush and Viles 2007). Loss of housing due to extreme events and shifts in climate patterns is linked to displacement, loss of home-based businesses, and health and security issues (IPCC 2014b citing Haines et al. 2013). Some of the climate impacts described here (e.g., property damage associated with greater flood risk) are sometimes described as costs of carbon in analyses of the social cost of carbon (National Academies of Sciences, Engineering, and Medicine 2017b).

Climate change will also affect urban public services such as healthcare and social care services, education, police, and emergency services (IPCC 2014b citing Barata et al. 2011). The links between city sectors can mean that climate stressors have cascading impacts across sectors; these impacts increase risk to urban dwellers' health and well-being and make urban areas more vulnerable to disruptions (GCRP 2018a; GCRP 2018a citing Torres and Maletjane 2015). Water shortages can lead to reliance on poorer quality water sources and can increase the likelihood of contracting waterborne illnesses. Changes in temperature extremes will also impact health through heat stress (IPCC 2014b) and changes in air quality (IPCC 2014b citing Athanassiadou et al. 2010); however, impacts of climate change on air quality in particular locations are highly uncertain (IPCC 2014b citing Jacob and Winner 2009 and Weaver et al. 2009).

Adaptation

Adapting urban centers will require substantial coordination between the private sector, multiple levels of government, and civil society (GCRP 2018a; GCRP 2018a citing Department of the Interior Strategic Sciences Group 2013, C40 Cities Climate Leadership Group and Arup 2015, and Arup et al. 2013), but early action by urban governments is key to successful adaptation since adaptation measures need to be integrated into local investments, policies, and regulatory frameworks (IPCC 2014b). Existing risk reduction plans, such as public health and natural hazard mitigation plans, provide strong foundations for the development of more comprehensive and forward-thinking documents that address increasing exposure and vulnerability (IPCC 2014b). Embedding adaptation into existing plans and decision-making processes (e.g., multi-hazard mitigation plans, long-term water plans, permitting review processes) helps to institutionalize adaptation (Aylett 2015; GCRP 2018a citing Bierbaum et al. 2013, Hughes 2015, and Rosenzweig et al. 2015). Taking a long-term view toward planning is important so that future climate impacts do not undermine plans put in place now (GCRP 2018a).

Financing adaptation strategies could be one of the largest hurdles to overcome; however, urban adaptation can enhance the economic competitiveness of an area by reducing risks to businesses, households, and communities (IPCC 2014b). Additionally, there are emerging synergistic options for urban adaptation measures that also deliver GHG emissions reductions co-benefits (IPCC 2014b).

Rural Areas

This section defines rural areas and describes the existing conditions and potential vulnerability to climate change impacts. There is no clear definition of rural areas—frequently, rural areas are simply defined as areas that are not urban (IPCC 2014b citing Lerner and Eakin 2010). A consistent definition is difficult to reach because human settlements exist along a continuum from urban to rural with many varied land use forms in-between and varying development patterns between developed and developing countries. In general, IPCC and this SEIS accept the definitions of urban and rural used by individual countries and individual academic authors in their work.

Rural areas account for almost half of the world's total population and an even greater percentage of people in developing countries (IPCC 2014b citing UN DESA Population Division 2013). The U.S. Census Bureau classifies more than 95 percent of the land area in the United States as rural but only 19 percent of the population calls these areas home (GCRP 2014 citing HRSA 2012, U.S. Census Bureau 2012a, 2012b, USDA 2012). In the United States, modern rural populations are generally more vulnerable to climate change impacts due to various socioeconomic factors (e.g., age, income, education) (GCRP 2014).

Rural areas are subject to unique vulnerabilities to climate change due to their dependence on natural resources, their reliance on weather-dependent activities, their relative lack of access to information, and the limited amount of investment in local services (GCRP 2018a; IPCC 2014b). These rural vulnerabilities also have the potential to affect urban areas significantly; for example, rural areas in the United States provide much of the rest of the country's food, energy, water, forests, and recreation (GCRP 2014 citing ERS 2012).

Observed and Projected Climate Impacts

Rural livelihoods are less diverse than their urban counterparts are and are frequently dependent on natural resources that have unknown future availability such as agriculture, fishing, and forestry (GCRP

2014, 2018a; IPCC 2014b). In addition, communities that rely on mining and extraction will be affected by changes in the water, energy, and transportation sectors (IPCC 2014b; GCRP 2014). Due to this lack of economic diversity, climate change will place disproportionate stresses on the stability of these rural communities (GCRP 2014). The impacts of climate change will be amplified by the impacts on surrounding sectors within rural communities' spheres of life, such as impacts on economic policy, globalization, environmental degradation, human health, trade, and food prices (IPCC 2014b citing Morton 2007 and Anderson et al. 2010).

Events that have a negative impact on rural areas include tropical storms that can lead to sudden flooding and wind damage, droughts and temperature extremes that can increase water scarcity and thus kill livestock and affect agricultural yields (IPCC 2014b citing Handmer et al. 2012; Ericksen et al. 2012), inland flooding, sea-level rise, and wildfires (Hales et al. 2014; Gowda et al. 2018).

Rural areas frequently depend on groundwater extraction and irrigation for local agriculture (IPCC 2014b citing Lobell and Field 2011). Reduced surface water would increase the stress on groundwater and irrigation systems (GCRP 2014). Around the world, competition for water resources will increase with population growth and other uses such as energy production (IPCC 2014b; GCRP 2014). For example, high temperatures increase energy demand for air conditioning, which leads to increased water withdrawal for energy production. At the same time, the heat also dries out the soil, which increases irrigation demands (GCRP 2014).

For more information on climate impacts on livestock, fisheries, and agriculture, see the section entitled *Food, Fiber, and Forest Products*. Nonfood crops and high-value food crops such as cotton, rice, corn, wheat, wine grapes, beverage crops (coffee, tea, and cocoa), and other cash crops contribute to an important source of income to rural locations. While these crops tend to receive less study than staple food crops (IPCC 2014b), negative impacts of climate change on a variety of crop types have already been documented (GCRP 2014).

Impacts of climate change on rural infrastructure are similar to those in urban areas (see the section entitled *Urban Areas*) but frequently there is less redundancy in the system, so assets are more vulnerable to hydroclimatic events (GCRP 2014, 2018a; IPCC 2014b citing NRC 2008). Rural communities are becoming more connected to urban ones, but human migration from rural to urban areas is not necessarily any greater due to climate change than under regular conditions. This diverges from previous assumptions of increased migration (IPCC 2014b). Migration will increase following extreme events that lead to the desertion of local communities (e.g. extreme storms), but migration from slow environmental degradation (e.g., sea-level rise) is anticipated to be minimal. Generally, more migration is linked to additional stressors such as political instability and socioeconomic factors (IPCC 2014b citing van der Geest 2011). It is possible that factors such as increased temperatures and natural disasters will spur migration, but the underlying force may be the adverse consequences of climate change on agriculture (Bohra-Mishra et al. 2017).

There is a strong link between biodiversity, tourism, rural livelihoods, and rural landscapes in both developed and developing countries (IPCC 2014b citing Nyaupane and Poudel 2011, Scott et al. 2007, Hein et al. 2009, Wolfsegger et al. 2008, and Collins 2008). Tourism patterns could be affected by changes to the length and timing of seasons, temperature, precipitation, and severe weather events (GCRP 2014). Changes in the economic values of traditional recreation and tourism locations will affect rural communities because tourism makes up a significant portion of rural land use (IPCC 2014b citing Lal et al. 2011). Coastal tourism is vulnerable to cyclones and sea-level rise (IPCC 2014b citing Klint et al.

2012 and Payet and Agricole 2006) as well as beach erosion and saline intrusion (IPCC 2014b). Nature-based tourism may be affected by declining biodiversity and harsher conditions for trekking and exploring (IPCC 2014b citing Thuiller et al. 2006 and Nyaupane and Chhetri 2009). Winter sport tourism may be affected by declining snow packs and precipitation falling more frequently as rain rather than snow due to warmer temperatures (IPCC 2014b).

Adaptation

Rural adaptation will build on community responses to past climate variability; however, this could not be enough to allow communities to fully cope with climate impacts (IPCC 2014b). Temporary responses to food and water shortages or extreme events could even increase the long-term vulnerability of a community. For example, in Malawi, forest resources are used for coping with food shortages, but this deforestation enhances the community's vulnerability to flooding (IPCC 2014b citing Fisher et al. 2010). Successful adaptation should allow for the development of long-term strategies that not only respond to climate events but also minimize future vulnerabilities (IPCC 2014b citing Vincent et al. 2013).

Adaptation in rural communities also faces challenges posed by the lack of economic diversity, relatively limited infrastructure and resources, and decreased political influence (GCRP 2018a citing U.S. House of Representatives 2017, Kuttner 2016, and Williamson et al. 2012). Funding for adaptation in rural areas could be linked to other development initiatives that aim to reduce poverty or generally improve rural areas (IPCC 2014b citing Nielsen et al. 2012, Hassan 2010, and Eriksen and O'Brien 2007).

Human Health

This section provides an overview of the recent findings regarding observed and projected impacts of climate change on the human health sector in the United States and globally. This section describes the climate impacts related to extreme events, heat and cold events, air quality, aeroallergens, water- and food-borne diseases, vector-borne diseases, cancer, and indirect impacts on health. Effects of climate change on human health range from direct impacts from extreme temperatures and extreme weather events to changes in prevalence of diseases, and indirect impacts from changes to agricultural productivity, nutrition, conflict, and mental health. Across all potential impacts, disadvantaged groups such as children, elderly, sick, and low-income populations are especially vulnerable (Watts et al. 2019). Climate change is expected to exacerbate some existing health threats and create new challenges, and a greater number of people could be exposed (GCRP 2018a). At the same time, climate change could decrease the capacity of health systems to manage changes in health outcomes due to climate shifts.

Observed and Projected Climate Impacts

Health impacts associated with climate-related changes in exposure to extreme events (e.g., floods, droughts, heat waves, severe storms) include death, injury, illness, or exacerbation of underlying medical conditions. Climate change will increase exposure risk in some regions of the United States due to projected increases in frequency and intensity of drought, wildfires, and flooding related to extreme precipitation, rising temperatures, and hurricanes (EPA 2021j).

Many types of extreme events related to climate change cause disruption to infrastructure—including power, heating, ventilation and air conditioning systems, water, transportation, and communication systems—that are essential to maintaining access to health care and emergency response services that safeguard human health (EPA 2021j; GCRP 2016). The damage caused by extreme events can disrupt transportation and access to health services, which exacerbates health conditions of those chronically sick (GCRP 2016).

Across climate risks, those experiencing discrimination, low-income populations, some communities of color, and older adults and children often experience disproportionate health impacts (Ebi et al. 2018). Populations with greater health and social vulnerability often have less access to resources, information, institutions, or other factors that could help avoid or prepare for the health risks of climate change (Ebi et al. 2018).

One direct way that climate change is projected to affect human health is through increasing exposure to extreme heat, which is the leading source of weather-related deaths in the United States (Nahlik et al. 2017; Sailor et al. 2019). Hospital admissions and emergency room visits tend to increase during hot days with heat-related illnesses, including cardiovascular and respiratory complications, renal failure, electrolyte imbalance, and kidney stones (GCRP 2018a). These hospitalizations come at a monetary cost to patients, who are more likely to be adults over 65 years, African-Americans, Asians/Pacific Islanders, and women (Schmeltz et al. 2016). Higher than usual temperatures can cause heat exhaustion and heat stroke, and exacerbate other cardiovascular and pulmonary conditions (Mora et al. 2017a; Tianqi et al. 2017 citing Borden and Cutter 2008, Bouchama et al. 2007, and Wilker et al. 2012).

Certain populations are more vulnerable to extreme heat events than others. In general, those with pre-existing conditions are more vulnerable to heat-related illness (Kuehn and McCormick 2017). In all parts of the world, the youngest, oldest, and poorest members of society are most vulnerable to health impacts from heat and cold events (EPA 2021j; GCRP 2016). Pregnant women and their fetuses are particularly vulnerable to the impacts of heat exposure because their thermoregulatory abilities are limited. Increased heat events could increase preterm birth, decrease birth weights, and increase the rate of stillbirths (Kuehn and McCormick 2017). Higher temperatures and humidity can create negative health outcomes for people engaging in physical activity, or for those who work outside (IPCC 2018). Worker safety and productivity during the hottest days and months will be a greater challenge under a changing climate (IPCC 2018). Certain geographic areas are more likely to experience damaging heat events. For example, the risk of heat waves will be higher in cities as a result of the urban heat island effect (IPCC 2018; GCRP 2018a). Additionally, increased mortality from extreme heat exposure will be more marked in regions that are currently warmer and poorer, particularly around the equator (Gasparrini et al. 2017; Mora et al. 2017a). With 1.5°C of warming, twice as many megacities will be exposed to heat stress, which would expose approximately 350 million additional people to dangerous heatwave conditions by 2050 (IPCC 2018). Globally, roughly 30 percent of the world's population is exposed to potentially deadly heat conditions. This is projected to increase to about 48 percent under a moderate emissions scenario (RCP4.5) and up to 74 percent under a high emissions scenario (RCP8.5) by 2100 (Mora et al. 2017).

The reduction in cold-related deaths has not been studied as thoroughly as heat-related deaths, although such events have become less frequent and intense, and they are expected to continue to decrease (GCRP 2016). Warming associated with climate change could contribute to a decline in cold-related deaths, but evidence suggests that the impacts from extreme heat events greatly outweigh any benefits from decreases in cold-related deaths (GCRP 2018a; EPA 2021j, 2015c; IPCC 2014b citing Ebi and Mills 2013 and Kinney et al. 2010; Medina-Ramón and Schwartz 2007; GCRP 2014 citing Yu et al. 2011 and Li et al. 2013; Hajat et al. 2014; GCRP 2016 citing Mills et al. 2012, Deschênes and Greenstone 2011, Barreca 2012, and Honda et al. 2014).

Although CO_2 emissions do not directly affect air quality, increased temperatures and related climate changes due to emissions of CO_2 and other GHGs could increase the formation of ozone and particulate matter 2.5 microns or less in diameter (PM2.5) and affect their dispersion and transport, affecting ozone and PM2.5 concentrations. Climate change could increase ground-level concentrations of ozone or PM in some locations, thus degrading air quality and negatively affecting human health (Section 4.1.1.1, *Health Effects of Criteria Pollutants*), as well as being associated with developmental problems such as childhood attention deficit hyperactivity disorder (Perera 2017 citing Newman et al. 2013; Perera et al. 2014). Ozone formation is temperature-dependent and increases in ozone levels could result in more ozone-related mortality (IPCC 2018). Climate change may result in meteorological conditions more favorable for the formation of ozone, including higher temperatures, less relative humidity, and altered wind patterns (Jacob and Winner 2009; GCRP 2016). Ozone production could increase with rising temperatures, especially in urban areas (IPCC 2014b citing Chang et al. 2010, Ebi and McGregor 2008, Polvani et al. 2011, and Tsai et al. 2008). These climate-driven increases in ozone could cause premature deaths, hospital visits, lost school days, and acute respiratory symptoms (GCRP 2016; Silva et al. 2017).

As with ozone, climate change is expected to alter several meteorological factors that affect PM2.5, including precipitation patterns, wind patterns and atmospheric mixing, and humidity, although there is less consensus regarding the effects of meteorological changes on PM2.5 than on ozone (Jacob and Winner 2009; GCRP 2016 citing Dawson et al. 2014). Because of the strong influence of changes in precipitation and atmospheric mixing on PM2.5 levels and because of the high variability in projected changes to those variables, it is not yet clear whether climate change will lead to a net increase or decrease in PM2.5 levels in the United States (GCRP 2016 citing Dawson et al. 2014, Fiore et al. 2012, Penrod et al. 2014, Tai et al. 2012, Val Martin et al. 2015, Dawson et al. 2009, and Trail et al. 2014). Overall, however, eastern, midwestern, and southern states are projected to experience degraded air quality associated with climate change (EPA 2015c; GCRP 2016).

Climate change can also affect air quality through an increasing number of wildfires and changing precipitation patterns. Wildfires produce PM pollutants and ozone precursors that diminish both air quality and human health (EPA 2021j; GCRP 2016; Reid et al. 2016, 2019). The public health burden (in terms of number and economic value of wildfire morbidity and mortality) is "considerable," with an economic value of up to $20 billion from short-term exposure cases and up to $130 billion for long-term exposure cases (in 2010 dollars) (Fann et al. 2018). Climate change could also affect air quality through changes in vegetative growth, increased summertime stagnation events, and increased absolute humidity (GCRP 2014 citing Peel et al. 2013). Further, climate change is projected to increase flooding in some locations both in the United States (GCRP 2014 citing IPCC 2007b and IPCC 2012) and around the world (IPCC 2014b citing IPCC 2012). Combined with higher air temperatures, this could foster the growth of fungi and molds, diminishing indoor air quality, particularly in impoverished communities (GCRP 2014 citing Fisk et al. 2007, Institute of Medicine 2011, Mudarri and Fisk 2007, and Wolf et al. 2010).

Increased temperatures and CO_2 concentrations can shift or extend plant growing seasons, including those of plants that produce allergens and pollen (EPA 2021j; GCRP 2014 citing Sheffield et al. 2011a, Emberlin et al. 2002, Pinkerton et al. 2012, Schmier and Ebi 2009, Shea et al. 2008, Sheffield and Landrigan 2011, and Ziska et al. 2011; Hjort et al. 2016). These effects already occur worldwide and are projected to continue with climate change (D'Amato et al. 2013; GCRP 2014; IPCC 2014b). Increases in pollen and other aeroallergens can exacerbate asthma and other health problems such as conjunctivitis and dermatitis (EPA 2021j; IPCC 2014b citing Beggs 2010). Exposure to air pollutants such as increased ozone or PM levels could also exacerbate the effects of aeroallergens (GCRP 2016 citing Cakmak et al.

2012). Increases in aeroallergens has also been known to reduce school and work productivity (GCRP 2014 citing Ziska et al. 2011, Sheffield et al. 2011b, and Staudt et al. 2010).

Climate—both temperature and precipitation—can influence the growth, survival, and persistence of water- and food-borne pathogens (EPA 2021j; IPCC 2014b). Also, changing weather patterns may shift the geographic range, seasonality, and intensity of climate-sensitive infectious disease transmission (IPCC 2018). For example, heavy rainfall and increased runoff promote the transmission of water-borne pathogens and diseases in recreational waters, shellfish-harvesting waters, and sources of drinking water with increased pathogens and toxic algal blooms (GCRP 2018a; EPA 2021j; GCRP 2016). Diarrheal disease rates are also linked to temperatures (IPCC 2014b). More frequent and intense rainfall and storm surge events could lead to combined sewer overflows that can contaminate water resources, (GCRP 2018a; EPA 2021j; IPCC 2014b citing Patz et al. 2008) and changes in streamflow rates can precede diarrheal disease outbreaks like salmonellosis and campylobacteriosis (GCRP 2014 citing Harper et al. 2011 and Rizak and Hrudey 2008; GCRP 2016). In general, heavy rainfall, flooding, and high temperatures are associated with higher rates of diarrheal disease (GCRP 2018a). Rising water temperatures could also increase the growth and abundance of pathogens in coastal environments that cause illnesses and deaths from both water contact and ingestion of raw or undercooked seafood. Changes in ocean pH may also increase virulent strains of pathogens prevalent in seafood, particularly because acidification can increase the proliferation of microbes that affect shellfish, whose immune responses and shells are weakened, making them more susceptible to infection (NIH 2010). Higher temperatures are expected to increase Vibrio, a temperature-sensitive and dangerous marine pathogen (GCRP 2018a; Muhling et al. 2017). Climate change-induced drought may increase the spread of pests and mold that can produce toxins dangerous to consumers (NIH 2010 citing Gregory et al. 2009). Similar to other climate change health impacts, children and the elderly are most vulnerable to serious health consequences from water- and food-borne diseases that could be affected by climate change (GCRP 2014). In 2015, an estimated 688 million illnesses and 499,000 deaths of children under 5 years of age were attributed to diarrheal diseases worldwide, making it the second leading cause of death for this age group (Kotloff et al. 2017 citing GBD 2015).

Climate change, particularly changes in temperatures, could change the range, abundance, and disease-carrying ability of disease vectors such as mosquitoes or ticks (GCRP 2018a; EPA 2021j; IPCC 2014b; Bouchard et al. 2019; GCRP 2016). This, in turn, could affect the prevalence and geographic distribution of diseases such as Rocky Mountain spotted fever, plague, tularemia, malaria, dengue fever, chikungunya virus, Lyme disease, West Nile virus, and Zika virus in human populations (Watts et al. 2017; GCRP 2014 citing Mills et al. 2010, Diuk-Wasser et al. 2010, Ogden et al. 2008, Keesing et al. 2009, The Community Preventive Services Task Force 2013, Degallier et al. 2010, Johansson et al. 2009, Jury 2008, Kolivras 2010, Lambrechts et al. 2011, Ramos et al. 2008, Gong et al. 2011, Morin and Comrie 2010, Centers for Disease Control 2012, and Nakazawa et al. 2007). Some of these changes are already occurring, although the interactions between climate changes and actual disease incidence are complex and multifaceted (Altizer et al. 2013; Deichstetter 2017). Climate change could also alter temperature, precipitation, and cloud cover, which can affect sun exposure behavior and change the risk of ultraviolet (UV) ray-related health outcomes. However, UV exposure is influenced by several factors, and scientists are uncertain whether it will increase or decrease because of climate change (IPCC 2014b citing van der Leun et al. 2008, Correa et al. 2013, and Belanger et al. 2009).

Climate change can influence mental health. People can experience adverse mental health outcomes and social impacts from the threat of climate change, the perceived direct experience of climate change, and changes to the local environment (EPA 2021j). Climate change is associated with mental health consequences ranging from stress to clinical disorders, such as anxiety, depression, post-traumatic stress disorder, and thoughts and acts of suicide (GCRP 2018a; Burke et al. 2018; Khafaie et al. 2019). Extreme weather conditions can increase stress population-wide, which can exacerbate preexisting mental health problems and even cause such conditions (EPA 2021j; IPCC 2014b). For example, individuals experiencing loss due to flood or risk of flood report high levels of depression and anxiety, which could persist for years after the event (GCRP 2018a). Children, the elderly, women, people with preexisting mental illness, the economically disadvantaged, Indigenous communities, the homeless, and first responders are at higher risk for distress and adverse mental health consequences from exposure to climate-related disasters (GCRP 2018a; EPA 2021j; GCRP 2016 citing Osofsky et al. 2011 and Schulte et al. 2016).

Environmentally motivated migration and displacement may lead to disruption of social ties and community bonds, which may negatively affect mental health, for both those displaced and those who stay behind (Torres and Casey 2017). Stress, induced by climate change or other factors, can also result in pregnancy-related problems such as preterm birth, low birth weight, and maternal complications (Harville et al. 2009; GCRP 2014 citing Xiong et al. 2008; GCRP 2016 citing Sheffield and Landrigan 2011; Rylander et al. 2013). Heat can also affect mental health and has been known to increase aggressive behaviors, in addition to increasing suicide rates, dementia, and problems for patients with schizophrenia and depression (GCRP 2018a; EPA 2021j; GCRP 2014 citing Bouchama et al. 2007, Bulbena et al. 2006, Deisenhammer 2003, Hansen et al. 2008, Maes et al. 1994, Page et al. 2007, Basu and Samet 2002, Martin-Latry et al. 2007, and Stöllberger et al. 2009; GCRP 2016 citing Ruuhela et al. 2009, Dixon et al. 2007, Qi et al. 2009, and Preti et al. 2007).

Climate change can also affect human exposure to toxic chemicals such as arsenic, mercury, dioxins, pesticides, pharmaceuticals, algal toxins, and mycotoxins through several pathways (Balbus et al. 2013).

Adaptation

IPCC (2014b) characterizes three tiers of adaptation: incremental adaptation, transitional adaptation, and transformational adaptation. Incremental adaptation covers improvements to basic public health and healthcare services, such as vaccination programs and post-disaster initiatives (IPCC 2014b). Transitional adaptation refers to policies and measures that incorporate climate change considerations, such as vulnerability mapping, while transformational adaptation involves more drastic system-wide changes and has yet to be implemented in the health sector (IPCC 2014b).

The public health community has identified several potential adaptation strategies to reduce the risks to human health from climate change. The Centers for Disease Control and Prevention has established the Building Resilience against Climate Effects Framework, which can help health officials assess how climate impacts could affect disease burdens and develop a Climate and Health Adaptation Plan. The framework aligns with the Climate-Ready States and Cities Initiative, which, as of June 2018, is working with 16 states and two cities to project future health impacts and develop programs to address them. The program provides resources for states, cities, and municipalities to develop their own climate and health adaptation plans, including concept documents, toolkits, webinars, and data resources.

At the state level, governments can conduct vulnerability and adaptation assessments, develop emergency response plans for climate events, develop climate-proof healthcare infrastructure, and integrate surveillance systems for infectious disease (IPCC 2018).

In terms of specific adaptation measures, early warning programs can be cost-effective ways to reduce human health impacts from extreme weather events (GCRP 2014 citing Chokshi and Farley 2012, Kosatsky 2005, Rhodes et al. 2010, and The Community Preventive Services Task Force 2013). Heatwave early-warning systems can also be used to reduce injuries, morbidity, and mortality due to heatwaves (IPCC 2018). A local adaptation strategy may include opening a community cooling center during heat waves to accommodate vulnerable and at-risk populations (Nayak et al. 2017). In the long term, strategies to reduce the urban heat island effect such as cool roofs and increased green space can reduce health risks from extreme heat (GCRP 2014 citing Stone et al. 2010 and EPA 2012b; Boumans et al. 2014; McDonald et al. 2016). GHG reduction policies can also create co-benefits for air pollution by reducing pollutants, such as PM, SO_2, nitrogen dioxide, and other harmful pollutants (IPCC 2018). Thus, mitigation strategies can have health benefits by improving air quality and promoting active transportation, which can reduce rates of obesity, diabetes, and heart disease (GCRP 2014 citing Markandya 2009 and Haines et al. 2009).

Human Security

This section provides an overview of the recent findings regarding observed and projected impacts of climate change on human security in the United States and globally. IPCC defines human security in the context of climate change as "a condition that exists when the vital core of human lives is protected, and when people have the freedom and capacity to live with dignity" (IPCC 2014b). As there are multiple drivers of human security, it can be difficult to establish direct causation between climate change and impacts on human security. The connections between climate and national security are complex because national security can be affected by a variety of secondary impacts such as resource scarcity and competition (GCRP 2018a). Rather than directly causing conflict, climate stress could drive changes in commodity prices or food and water insecurity, which are drivers of conflict (GCRP 2018a). Overall, the research literature finds that climate change has negative impacts on various dimensions of human security, including livelihoods, food, water, cultures, migration, and conflict. However, some dimensions of human security are driven more by economic and social forces rather than by climate change (IPCC 2014b). As the Department of Defense concluded in a 2015 report to Congress, climate change may have far-reaching impacts on existing problems, such as poverty, social tensions, environmental degradation, ineffectual leadership, and weak political institutions both nationally and internationally (DOD 2015).

Observed and Projected Climate Impacts

Economic and livelihood security includes access to food, clean water, shelter, employment, and avoidance of direct risks to health. Climate change poses significant risks to all of these aspects and can thereby threaten the economic and livelihood security of individuals or communities (IPCC 2014b). Even with an increase of approximately 1.5°C by 2030, climate change will be a "poverty multiplier" that increases levels of poverty and the number of people living in poverty (IPCC 2018 citing Hallegatte et al. 2016 and Hallegatte and Rozenberg 2017). In particular, climate change will affect those whose livelihoods depend on natural resources (Brzoska and Frohlich 2015; Reyer et al. 2017). There are well-documented impacts of climate variability and change on agricultural productivity and food insecurity, water stress and scarcity, and destruction of property and residence (IPCC 2014b citing Carter et al. 2007, Leary et al. 2008, Peras et al. 2008, Paavola 2008, and Tang et al. 2009). Populations that are most at risk of food insecurity include the urban poor and the rural and indigenous communities whose livelihoods are highly dependent upon natural resources (GCRP 2014, 2018a).

Around the world, it is increasingly challenging for indigenous communities to maintain cultures, livelihoods, and traditional food sources in the face of climate change (IPCC 2014b citing Crate and Nuttall 2009 and Rybråten and Hovelsrud 2010; GCRP 2014 citing Lynn et al. 2013). The impacts of climate change are expected to be more significant in places where indigenous people live and on traditional ecological knowledge (IPCC 2018 citing Olsson et al. 2014). Many studies indicate that further significant changes in the natural resource base would negatively affect indigenous cultures, particularly if people are confined to particular territories created by treaties; if natural resources are lost within that territory, that is a permanent loss to the tribe and their culture (GCRP 2018a; IPCC 2014b citing Crate 2008, Gregory and Trousdale 2009, and Jacka 2009). For example, climate change is causing changes in the range and abundance of culturally important plant and animal species, reducing the availability of and access to traditional foods, and increasing damage to tribal homes and cultural sites (GCRP 2014 citing Lynn et al. 2013, Voggesser et al. 2013, and Karuk Tribe 2010). Ultimately, this could make life on ancestral lands untenable (IPCC 2018). In addition, traditional practices are already facing multiple stressors, such as changing socioeconomic conditions and globalization, which undermine their ability to adapt to climate change (IPCC 2014b citing Green el al. 2010). Climate change can also cause loss of land and displacement, such as in small island nations or coastal communities, which have well-documented negative cultural and well-being impacts (IPCC 2014b citing Bronen 2011, Johnson 2012, Arnall 2013, Bronen 2010, Bronen and Chapin 2013, and Cunsolo-Willox et al. 2012, 2013).

The efficacy of traditional practices can be eroded "when governments relocate communities" (IPCC 2014b citing Hitchcock 2009, McNeeley 2012, and Maldonado et al. 2013); "if policy and disaster relief creates dependencies" (IPCC 2014b citing Wenzel 2009 and Fernández-Giménez et al. 2012); "in circumstances of inadequate entitlements, rights, and inequality" (IPCC 2014b citing Shah and Sajitha 2009 and Green et al. 2010; GCRP 2014 citing Lynn et al. 2013); and "when there are constraints to the transmission of language and knowledge between generations" (IPCC 2014b citing Forbes 2007) (IPCC 2014b). Lack of involvement in formal government decision-making over resources also decreases the resilience of indigenous peoples and their cultures to climate change impacts (IPCC 2014b citing Ellemor 2005, Brown 2009, Finucane 2009, Turner and Clifton 2009, Sánchez-Cortés and Chavero 2011, and Maldonado et al. 2013).

Climate change is expected to increase internal migration and displacement, in part due to extreme events or long-term environmental changes (IPCC 2018 citing Albert et al. 2017; Heslin et al. 2019). However, the causation and extent of this risk is hard to determine due to the complexity of migration decisions (IPCC 2018). Much of the literature reviewed in the IPCC *Special Report on Extreme Events* suggests that an increase in the incidence and/or severity of extreme events due to climate change will directly increase the risks of displacement and amplify its impacts on human security (IPCC 2014b). Projections indicate that 4.2 million Americans could be at risk with 3 feet of sea-level rise, and 13.1 million people with 6 feet of sea-level rise, which could drive mass migration and societal disruption (Hauer 2017; Hauer et al. 2016). In the past, major extreme weather events have led to significant population displacement (IPCC 2014b). For example, after Hurricane Katrina, refugees from coastal areas spread to all 50 states, which resulted in economic and social costs around the country (GCRP 2018a). Following rapid-onset events such as floods or storms, such displacement is usually short-term (Brzoska and Frohlich 2015). Most displaced people try to return to their original residence and rebuild as soon as circumstances allow (IPCC 2014b). As a result, only a portion of displacement leads to permanent migration (IPCC 2014b citing Foresight 2011 and Hallegatte 2012).

Climate-driven migration outside of the United States could have implications for national security, either due to immigrants to the United States or instability abroad. For example, there could be significant population displacement in the tropics due to warming. Tropical populations may have to move more than 1,000 kilometers by the end of the century, which could lead to a concentration of displaced persons on the margins, contributing to higher population densities in destination areas (IPCC 2018 citing Hsiang and Sobel 2016). Some of these refugees could come to the United States. For example, the United States granted Temporary Protected Status to 57,000 Honduran and 2,550 Nicaraguan nationals after Hurricane Mitch (GCRP 2018a).

Long-term changes in climate conditions, such as droughts or land degradation, have greater potential to result in permanent migration (Brzoska and Frohlich 2015). For example, higher temperatures have contributed to outmigration in 163 countries, specifically for those dependent on agriculture (IPCC 2018 citing Cai et al. 2016). According to the International Migration Database of the Organisation for Economic Co-operation and Development, a 1°C increase in temperature contributed to a 1.9 percent increase in migration flows from 142 countries moving to 19 receiving countries, and an additional increase in precipitation of 1 millimeter could increase migration by 0.5 percent (IPCC 2018 citing Backhaus et al. 2015).

A number of studies have found that migrants can face increased risks due to climate change impacts in their new destinations, such as in cities (IPCC 2014b citing Black et al. 2011). Climate change-induced mass migration threatens to adversely affect the humanitarian assistance requirements of the U.S. military, as well as strain its ability to respond to conflict (DOD 2015; NRC 2011b). Displacement affects human security by affecting housing, health, and economic outcomes (IPCC 2014b citing Adams et al. 2009 and Hori and Shafer 2010). A large influx of migrants can also encourage violence, especially if the refugees differ from the native population in ethnicity, nationality, and/or religion; have had previous conflicts with the receiving area; or want to settle long term (Brzoska and Frohlich 2015). In other cases, migration to more prosperous and resource-rich areas can dissolve conflicts (Brzoska and Frohlich 2015).

Conversely, extreme events can sometimes be associated with immobility or in-migration instead of displacement. For example, Paul (2005) found that little displacement occurred following floods in Bangladesh and there was in-migration due to reconstruction activities (IPCC 2014b citing Paul 2005). As migration is resource-intensive, in some cases migration flows decreased when the households had limited resources, such as in drought years (IPCC 2014b citing Findley 1994, van der Geest 2011, and Henry et al. 2004). Often, lack of mobility is associated with increased vulnerability to climate change, as vulnerable populations frequently do not have the resources to migrate from areas exposed to the risks from extreme events. When migration occurs among vulnerable populations, it is usually an "emergency response that creates conditions of debt and increased vulnerability, rather than reducing them" (IPCC 2014b citing Warner and Afifi 2013).

The association between short-term warming and deviations in rainfall (including floods and droughts) with armed conflict is contested, with some studies finding a relationship while others finding no relationship (Schleussner et al. 2016; Buhaug et al. 2015; IPCC 2014b). Most studies find that climate change impacts on armed conflict is negligible in situations where other risk factors are extremely low, such as where per capita incomes are high or governance is effective and stable (IPCC 2014b citing Bernauer et al. 2012, Koubi et al. 2012, Scheffran et al. 2012, and Theisen et al. 2013). Many studies, however, argue that reduced availability and changes in the distribution of water, food, and arable land from a changing climate are factors prone to triggering violent conflicts (Brzoska and Frohlich 2015 citing Hsiang et al. 2013). Rather than a causal relationship between climate change and conflict, climate change is identified as a "threat multiplier" that exacerbates existing or arising threats to stability and peace and may trigger armed conflict (Buhaug 2016 citing CNA 2007). In summary, "there is justifiable common concern that climate change or changes in climate variability increases the risk of armed conflict in certain circumstances [...] even if the strength of the effect is uncertain" (IPCC 2014b citing Bernauer et al. 2012, Gleditsch 2012, Scheffran et al. 2012, and Hsiang et al. 2013). It is, however, not possible to make confident statements regarding the impacts of future climate change on armed conflict due to the lack of "generally supported theories and evidence about causality" (IPCC 2014b).

The potential impacts of climate change on accelerating instability in volatile regions of the world have profound implications for national security of the United States. The U.S. Department of Defense 2014 Quadrennial Defense Review indicates that the projected effects of climate change "... are threat multipliers that will aggravate stressors abroad such as poverty, environmental degradation, political instability, and social tensions—conditions that can enable terrorist activity and other forms of violence" (DOD 2015). For example, drought may increase the likelihood of sustained conflict, particularly for groups dependent on agricultural livelihoods, which are more vulnerable to climate change (IPCC 2018). With a 1°C increase in temperature or a greater intensity of extreme rainfall events, intergroup conflicts could increase in frequency by 14 percent (IPCC 2018 citing Hsiang et al. 2013).

Climate change can compromise state integrity by affecting critical infrastructure, threatening territorial integrity, and increasing geopolitical rivalry (IPCC 2014b). Climate change impacts on critical infrastructure will reduce the ability of countries to provide the economic and social services that are important to human security (IPCC 2014b). For example, extreme heat, storms and floods, and sea-level rise could directly affect military assets, such as roads, airport runways, and coastal infrastructure; disrupt supply chains; endanger personnel; inhibit training; and increase operating costs (GCRP 2018a). In addition, climate change can also affect military logistics, energy, water, and transportation systems, compromising the ability of the U.S. military to conduct its missions (NRC 2011b, 2013c; CNA Corporation 2014). Power outages and fuel shortages could affect the energy system, which could have cascading impacts on critical sectors that support the economy and national security (GCRP 2018a). Furthermore, the U.S. military could become overextended as it responds to extreme weather events and natural disasters at home and abroad, along with current or future national security threats (NRC 2011b; CNA Corporation 2014).

Sea-level rise, storm surge, and coastal erosion can threaten the territorial integrity of small island nations or countries with significant areas of soft low-lying coasts (IPCC 2014b citing Hanson et al. 2011, Nicholls et al. 2011, Barnett and Adger 2003, and Houghton et al. 2010). These changes can also have negative implications for navigation safety, port facilities, and coastal military bases (DOD 2015). Open access to resources and new shipping routes due to significant reductions in Arctic sea ice coverage could increase security concerns because of territorial and maritime disputes, if equitable arrangements between countries cannot be agreed to (DOD 2015; IPCC 2014b; GCRP 2014). A variety of maritime boundary disputes in the Arctic could be exacerbated by the increased accessibility of the region due to warmer temperatures (Smith and Stephenson 2013 citing Brigham 2011 and Elliot-Meisel 2009). Furthermore, nations bordering the Arctic maintain unresolved sea and economic zone disputes (Smith and Stephenson 2013 citing Liu and Kronbak 2010 and Gerhardt et al. 2010; NRC 2011b). Other transboundary impacts of climate change such as changing shared water resources and migration of fish stocks can increase geopolitical rivalry between countries (IPCC 2014b). Additionally, climate change could increase tension and instability over energy supplies (CNA Corporation 2014).

Adaptation

Adaptation strategies can reduce vulnerability and thereby increase human security. Examples of adaptation measures to improve livelihoods and well-being include diversification of income-generating activities in agricultural and fishing systems, development of insurance systems, and provision of education for women. Integration of local and traditional knowledge is found to increase the effectiveness of adaptation strategies. Improvements in entitlements and rights, as well as engagement of indigenous peoples in decision-making, increase their social and cultural resilience to climate change (IPCC 2014b). There is not enough evidence on the effectiveness of migration and resettlement as adaptation. Migration is costly and disruptive and is thus often perceived as an adaptation of last resort (IPCC 2014b citing McLeman 2009). Poorly designed adaptation strategies can increase the risk of conflict and amplify vulnerabilities in certain populations, if they exacerbate existing inequalities or grievances over resources (IPCC 2014b).

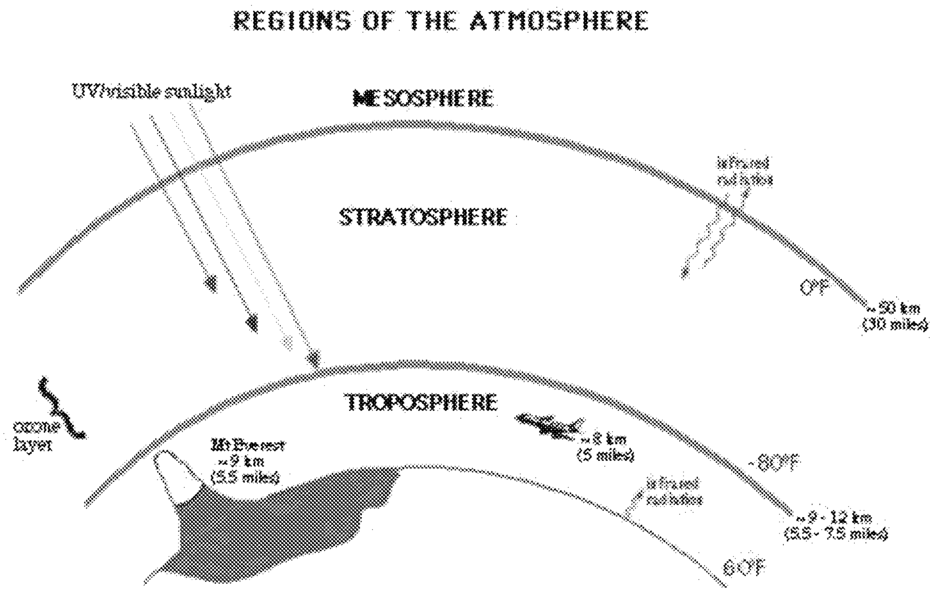
Local and traditional knowledge is a valuable source of information for adapting to climate change (IPCC 2014b; GCRP 2014). There is high agreement in the literature that the integration of local and traditional and scientific knowledge increases adaptive capacity (IPCC 2014b citing Kofinas et al. 2002, Oberthür et al. 2004, Tyler et al. 2007, Anderson et al. 2007, Vogel et al. 2007, West et al. 2008, Armitage et al. 2011, Frazier et al. 2010, Marfai et al. 2008, Flint et al. 2011, Ravera et al. 2011, Nakashima et al. 2012, and Eira et al. 2013). While being an important resource for adaptation, traditional knowledge may be insufficient to respond to rapidly changing ecological conditions or unexpected or infrequent risks (IPCC 2014b; GCRP 2014). As a result, current traditional knowledge strategies could be inadequate to manage projected climate changes (IPCC 2014b citing Wittrock et al. 2011). While adaptation is possible to avoid some losses of cultural assets and expressions, cultural integrity will still be compromised if climate change erodes livelihoods, sense of place, and traditional practices (IPCC 2014b).

Stratospheric Ozone

This section presents a review of stratospheric ozone and describes how CO_2 and climate change are projected to affect stratospheric ozone concentrations. Ozone is a molecule consisting of three oxygen atoms. Ozone near Earth's surface is considered an air pollutant that causes respiratory problems in humans and adversely affects crop production and forest growth (Fahey and Hegglin 2011). Conversely, ozone in Earth's stratosphere (approximately 9 to 28 miles above Earth's surface) acts as a shield to block UV rays from reaching Earth's surface (Ravishankara et al. 2008).[30] This part of the atmosphere is referred to as the *ozone layer*, and it provides some protection to humans and other organisms from exposure to biologically damaging UV rays that can cause skin cancer and other adverse impacts for humans and other organisms (Fahey and Hegglin 2011; Fahey et al. 2008; Figure 8.6.5-1).

[30] These height measurements defining the bottom and top of the stratosphere vary depending on location and time of year. Different studies might provide similar but not identical heights. The heights indicated for the stratosphere and the layers within the stratosphere are provided in this section as defined by each study.

Figure [STYLEREF 3 \s]-[SEQ Figure * ARABIC \s 3]. The Three Lowest Layers in Earth's Atmosphere and the Location of the Ozone Layer



Source: NOAA 2011
UV = ultraviolet; km = kilometers; °F – degrees Fahrenheit

Ozone in the stratosphere is created when a diatomic oxygen molecule absorbs UV rays at wavelengths less than 240 nanometers, causing the molecule to dissociate into two very reactive free radicals that then each combine with an available diatomic oxygen molecule to create ozone (Fahey and Hegglin 2011). Through this process, heat is released, warming the surrounding environment. Once ozone is formed, it absorbs incoming UV rays with wavelengths from 220 to 330 nanometers (Fahey and Hegglin 2011). Ozone, which is a very reactive molecule, could also react with such species as hydroxyl radical, nitric oxide, or chlorine (Fahey et al. 2008).

The concentration of ozone in the stratosphere is affected by many factors, including concentrations of ozone-depleting substances and other trace gases, atmospheric temperatures, transport of gases between the troposphere and the stratosphere, and transport within the stratosphere. Specifically, ozone is depleted in reactions that involve halogens, such as chlorine and bromine, which result from the decomposition of some halocarbons (GCRP 2017 citing WMO 2014). Alterations to the carbon cycle, including climate-driven ecosystem changes, influence atmospheric concentrations of CO_2 and CH_4. In turn, atmospheric aerosols affect clouds and precipitation rates, which change the removal rates, lifetimes, and abundance of the aerosols themselves (GCRP 2017 citing Nowack et al. 2015). Also, stratospheric ozone abundance can be affected by climate-driven circulation changes and longwave radiation feedbacks (GCRP 2017 citing Nowack et al. 2015).

IPCC reports it is *very likely* that anthropogenic contributions, particularly to GHGs and stratospheric ozone depletion, have led to the detectable tropospheric warming and related cooling in the lower stratosphere since 1961 (IPCC 2014b). Satellite and ground observations demonstrated clearly that stratospheric ozone was decreasing in the 1980s. There is an international consensus that human-made ozone-depleting substances (such as gases emitted by air conditioners and aerosol sprays) are responsible, which has prompted the establishment of international agreements to reduce the consumption and emissions of these substances (Fahey and Hegglin 2011; Langematz 2019). In response to these efforts, the rate of stratospheric ozone reduction has slowed. Although there are elements of uncertainty, stratospheric ozone concentrations are projected to recover to pre-1980 levels over the next several decades (Fahey and Hegglin 2011; WMO 2011), with further thickening of the ozone layer possible by 2100 in response to climate change (IPCC 2014b citing Correa et al. 2013).

Stratospheric ozone levels influence the surface climate in both the Northern and Southern Hemispheres. In the Northern Hemisphere, stratospheric ozone extremes over the Arctic contribute to spring surface temperatures, particularly linking low Arctic ozone in March with colder polar vortex and circulation anomalies (Ivy et al. 2017). March stratospheric ozone can be used as an indicator of spring climate in certain regions (Ivy et al. 2017). In the Southern Hemisphere, comparison of the 1979-2010 climate trends shows that stratospheric ozone depletion drives climate change (Li et al. 2016). Interactive chemistry causes cooling in the Antarctic lower stratosphere and acceleration of the circumpolar westerly winds (Li et al. 2016). In turn, this impacts overturning circulation in the Southern Ocean, leading to stronger ocean warming near the surface and increased ice melt around the Antarctic (Li et al. 2016). Changes in stratospheric ozone influence the climate by affecting the atmosphere's temperature structure and circulation patterns (Ravishankara et al. 2008). Conversely, climate change could aid in the recovery of stratospheric ozone. Although GHGs, including CO_2, warm the troposphere (the lower layer of the atmosphere), this process actually cools the stratosphere. Consequently, it slows the chemical reactions between stratospheric ozone and ozone-depleting substances, assisting in ozone recovery. Climate change could enhance atmospheric circulation patterns that affect stratospheric ozone concentrations, assisting in ozone recovery in the extra-tropics. However, for polar regions, cooling temperatures can increase winter polar stratospheric clouds, which are responsible for accelerated ozone depletion. In summary, reduced stratospheric ozone may contribute to climate change while climate change has been projected to have a direct impact on stratospheric ozone recovery, although there are large elements of uncertainty within these projections.

Human-Made Ozone-Depleting Substances and Other Trace Gases

Until the mid-1990s, stratospheric ozone concentrations had been declining in response to increasing concentrations of human-made ozone-depleting substances (WMO 2014). Since the year 2000, ozone has been slowly increasing in the upper stratosphere (Steinbrecht et al. 2017). Examples of ozone-depleting substances include chlorofluorocarbons and compounds containing chlorine and bromine (Ravishankara et al. 2008; Fahey and Hegglin 2011). These ozone-depleting substances are chemically inert near Earth's surface but decompose into very reactive species when exposed to UV radiation in the stratosphere.

In 1987, an international agreement, the Montreal Protocol on Substances that Deplete the Ozone Layer, was established to reduce the consumption and production of human-made ozone-depleting substances to protect and heal the ozone layer and rebuild the ozone hole.[31] Subsequent agreements have followed that incorporate more stringent reductions of ozone-depleting substances and expand the scope to include additional chemical species that attack ozone. Some ozone-depleting substances such as chlorofluorocarbons are potent GHGs; therefore, reducing the emissions of these gases also

[31] The polar regions experience the greatest reduction in total ozone, with about a 5 percent reduction in the Arctic and 18 percent reduction in the Antarctic (Fahey and Hegglin 2011). Significant thinning in the ozone layer has been observed above the Antarctic since the spring of 1985, to such a degree it is termed the *ozone hole* (Ravishankara et al. 2008). This location is particularly susceptible to ozone loss due to a combination of atmospheric circulation patterns, and the buildup of ozone-depletion precursors during the dark winter months from June to September.

reduces radiative forcing and hence reduces the heating of the atmosphere. However, HFCs were not included in the Montreal Protocol. Evidence shows that HFCs could contribute to anthropogenic climate change and, in 2016, the Kigali Amendment to the Montreal Protocol introduced a treaty on managing and phasing out HFCs (Hurwitz et al. 2016).

Increases in the emissions of other trace gases (e.g., CH_4 and nitrous oxide [N_2O]) and CO_2 affect stratospheric ozone concentrations (Fahey et al. 2008). When CH_4 is oxidized by hydroxyl radicals in the stratosphere, it produces water and the methyl radical. Increases in stratospheric water lead to an increase in reactive molecules that assist in the reduction of ozone and an increase in polar stratospheric clouds that accelerate ozone depletion. Increases in N_2O emissions cause a reduction of ozone in the upper stratosphere as N_2O breaks down into reactive ozone- depleting species.

Changes in Atmospheric Temperature

Since the observational record began in the 1960s, global stratospheric temperatures have been decreasing in response to ozone depletion, increased tropospheric CO_2, and changes in water vapor (Fahey et al. 2008). Natural concentrations of GHGs increase the warming in the troposphere by absorbing outgoing infrared radiation; increasing GHG concentrations in the troposphere traps more heat in the troposphere, which translates to less incoming heat into the stratosphere. In essence, as GHGs increase, the stratosphere is projected to cool. However, model simulations suggest reductions in ozone in the lower to middle stratosphere (13 to 24 miles) create a larger decrease in temperatures compared to the influence of GHGs (Fahey et al. 2008 citing Ramaswamy and Schwarzkopf 2002). Above a height of about 24 miles, both the reductions of ozone and the impact of GHGs can contribute significantly to stratospheric temperature decreases.

The cooling temperatures in the stratosphere could slow the loss of ozone (Fahey et al. 2008; Reader et al. 2013) because the dominant reactions responsible for ozone loss slow as temperatures cool. For example, ozone in the upper stratosphere is projected to increase by 15 to 20 percent under a doubled CO_2 environment (Fahey et al. 2008 citing Jonsson et al. 2004). In the lower stratosphere, where day-night energy transport plays an important role both within the stratosphere and between the troposphere and stratosphere, cooling temperatures have less influence on ozone concentrations (except in the polar regions). Since 1993, ozone in the lower stratosphere above the Arctic has been greatly affected by cooling temperatures, as cooling has led to an increase in polar stratospheric clouds (Fahey et al. 2008). Polar stratospheric clouds play a significant role in reducing ozone concentrations. Ozone in the lower stratosphere above the Antarctic does not demonstrate such a significant response to cooling temperatures because this region already experiences temperatures cold enough to produce these clouds.

Circulation and Transport Patterns

The large-scale Brewer-Dobson circulation represents the transport between the troposphere and stratosphere: an upward flux of air from the troposphere to the stratosphere occurs in the tropics balanced by a downward flux of air in the extratropics (the middle latitudes that extend beyond the tropics). This circulation carries stratospheric ozone from the tropics poleward. It is suggested that the ozone in the lower stratosphere has experienced an acceleration in this transport over the past century, particularly in the Northern Hemisphere—potentially explaining the larger increase in total atmospheric ozone per area (i.e., column ozone) observed in the Northern Hemisphere compared to the Southern Hemisphere (Reader et al. 2013). According to many chemistry-climate models and observational evidence, climate change is thought to accelerate the Brewer-Dobson circulation, thus extending the decline of ozone levels in the tropical lower stratosphere through the 21st century (WMO 2014).

Models suggest that the reduction of ozone above Antarctica is responsible for strengthening the circulation of stratospheric circumpolar winds of the wintertime vortex (i.e., the establishment of the vortex leads to significant ozone loss in late winter/early spring) (Fahey et al. 2008 citing Gillet and Thompson 2003 and Thompson and Solomon 2002).[32] Observations have shown that these winds can extend through the troposphere to the surface, leading to cooling over most of Antarctica. These studies suggest changes in stratospheric ozone can affect surface climate parameters.

Trends and Projections

Observations of global ozone concentrations in the upper stratosphere have shown a strong and statistically significant decline of approximately 6 to 8 percent per decade from 1979 to the mid-1990s (WMO 2011; Pawson and Steinbrecht 2014). Observations of global ozone within the lower stratosphere demonstrate a slightly smaller but statistically significant decline of approximately 4 to 5 percent per decade from 1979 to the mid-1990s (WMO 2014). An updated study from 2000 to 2016 found that ozone increased in the upper stratosphere by about 1.5 percent per decade in the tropics and by 2.5 percent per decade in the mid latitudes (35 to 60 degrees) (Steinbrecht et al. 2017). From 2000 to 2016 in the lower stratosphere, the trends are not statistically significant (Steinbrecht et al. 2017). The depletion of stratospheric ozone has been estimated to cause a slight radiative cooling of approximately -0.05 watts per square meter with a range of -0.15 to 0.05 watts per square meter, although there is great uncertainty in this estimate (Ravishankara et al. 2008).

WMO (2011) used 17 coupled chemistry-climate models to assess how total column ozone (i.e., the total ozone within a column of air from Earth's surface to the top of the atmosphere) and stratospheric ozone will change in response to climate change and reductions in ozone-depleting substances. Under a moderate (A1B) emissions scenario, the model ensemble suggests changes in climate will accelerate the recovery of total column ozone. The model ensemble suggests the northern mid-latitudes total column ozone will recover to 1980 levels from 2015 to 2030, and the southern mid-latitudes total column ozone will recover from 2030 to 2040. Overall, the recovery of total ozone to 1980 levels in the mid-latitudes is projected to occur 10 to 30 years earlier because of climate change. The Arctic has a similar recovery time to 1980 conditions, while the Antarctic will regain 1980 concentrations around mid-century (because the chemistry-climate models underestimate present-day Arctic ozone loss, the modeled Arctic recovery period might be optimistic). The recovery is linked to impacts of climate that affect total column ozone, including: increased formation of ozone in the mid-to-upper stratosphere in response to cooling temperatures, accelerated ground-level ozone formation in the troposphere as it warms, and an accelerated Brewer-Dobson circulation increase in ozone transport in the lower stratosphere from the tropics to the mid-latitudes (WMO 2014 citing WMO 2011).

In another study, doubled CO_2 concentrations simulated by 14 climate-change models project a 2 percent increase per decade in the annual mean troposphere-to-stratosphere exchange rate. This acceleration could affect long-lived gases such as chlorofluorocarbons, CH_4, and N_2O by reducing their lifetime and increasing their removal from the atmosphere. In addition, this could increase the vertical

[32] During the polar winter, a giant vortex with wind speeds exceeding 300 kilometers (186 miles) per hour can establish above the South Pole, acting like a barrier that accumulates ozone-depleting substances. In Antarctic springtime, temperatures begin to warm and the vortex dissipates. The ozone-depleting substances, now exposed to sunlight, release large amounts of reactive molecules that significantly reduce ozone concentrations (Fahey and Hegglin 2011).

transport of ozone concentrations from the stratosphere to the troposphere over mid-latitude and polar regions (Fahey et al. 2008 citing Butchart and Scaife 2001).

Compound Events

According to the IPCC, compound events consist of two or more extreme events occurring simultaneously or in sequence, the combination of one or more extreme events with underlying conditions that amplify the impact of the events, or combinations of events that are not themselves extremes but that collectively lead to extreme impacts when combined (IPCC 2012, 2019b). While some compound events may involve individual components that cancel one another out, others may include components with additive or even multiplicative effects (GCRP 2017). Compound events can also have societal impacts even if they occur across separate regions; for example, droughts in multiple agricultural areas could have amplifying effects on food shortages (GCRP 2017).

The underlying probability of compound events occurring may increase because of climate change, as underlying climate variables shift (GCRP 2017). Examples of shifting underlying conditions that could contribute to compound event frequency or severity include higher temperatures (of both surface and sea), increased drought risk, increased overall precipitation, and changes to oceanic circulation patterns (Cook et al. 2015; GCRP 2017; Swain et al. 2016). Climate change could also facilitate the emergence of new types of compound events by combining previously unseen physical effects (GCRP 2017). An example of this is Hurricane Sandy, which was affected by sea-level rise, anomalously high temperatures, and a so-called “blocking ridge” around Greenland that steered the storm toward the mainland and may have been caused by reduced summer sea ice in the region (GCRP 2017).

The interconnectedness of the ocean and cryosphere can also lead to a type of compounding event called a cascade, where changes in one event trigger and increase the likelihood of secondary changes in different but connected elements of the system (IPCC 2019a). For example, enhanced melting and mass loss from ice sheets creates a huge flux of freshwater and iron to the ocean, which can, in turn, have dramatic effects on ocean productivity. Similarly, increasing ocean temperatures and sea level can affect ice shelf, ice sheet, and glacier stability because of the nonlinear response of ice melt, and calving, to ocean temperatures (IPCC 2019a). In this case, small increases in ocean temperature have the potential to destabilize large sections of ice sheets and contribute to large sea-level rise changes (IPCC 2019a).

Climactic extremes in opposite directions can also form harmful compound events when occurring in sequence. For example, two major livestock and agricultural die-off events in Mongolia occurred in 1999–2002 and 2009–2010 when summer drought was immediately followed by extreme cold and heavy snowfall (IPCC 2012 citing Batjargal et al. 2001). Overall impacts of these events in Mongolia included a 33 percent loss in livestock and a 40 percent reduction in gross agricultural output as compared to previous years (IPCC 2012).

The impact of climate change on the frequency and severity of compound events remains uncertain because many climate models only address certain aspects of the climate system and cannot forecast compound events that involve combined forces from different subsystems (GCRP 2017; AghaKouchak et al. 2014). This makes the risks posed by compound events to be undervalued in modeled estimates of future climate conditions (GCRP 2017; AghaKouchak et al. 2014 citing Gräler et al. 2013).

To the extent the Proposed Action and alternatives would increase the rate of CO_2 emissions relative to the No Action Alternative, they would contribute to the general increased risk of extreme compound events. While this rulemaking alone would not cause increases in compound event frequency and severity from climate change, it would be one of many global actions that, together, could heighten these effects.

Tipping Points and Abrupt Climate Change

Tipping points refer to thresholds within Earth systems that could be triggered by continued increases in the atmospheric concentration of GHGs, incremental increases in temperature, or other relatively small or gradual changes related to climate change. Earth systems that contain a tipping point exhibit large or accelerating changes or transitions to a new physical state, which are significantly different from the rates of change or states that have been exhibited in the past, when the tipping point is crossed. A recent study suggests that passing some tipping points may increase the likelihood of occurrence of other tipping points (Cai et al. 2016). The following discussion provides examples of tipping points in Earth systems.

Climate feedbacks can also drive tipping points in the climate system. In particular, positive climate feedbacks amplify the impacts of anthropogenic emissions. For example, CO_2 emissions increase atmospheric temperatures, which increase the likelihood of wildfires that, in turn, release more CO_2 into the atmosphere (Liu et al. 2014). Climate feedbacks are complex and not always incorporated into future climate models, and could lead to tipping points being crossed earlier than anticipated.

Atlantic Meridional Overturning Circulation (AMOC)

The AMOC is the northward flow of warm, salty water in the upper layers of the Atlantic Ocean coupled to the southward flow of colder water in the deep layers, which transports oceanic heat from low to high latitudes. If enough freshwater enters the North Atlantic (such as from melting sea ice or the Greenland ice sheet), the density-driven sinking of North Atlantic waters might be reduced or even stopped, as apparently occurred during the last glacial cycle (approximately 22,000 years ago) (Lenton et al. 2008 citing Stocker and Wright 1991). This is expected to reduce the northward flow of thermal energy in the Gulf Stream and result in less heat transport to the North Atlantic. At the same time, reduced formation of very cold water may slow global ocean circulation, leading to impacts on global climate and ocean currents. A 2018 study indicates that these effects are underway, quantifying a 15 percent weakening since the mid-20th century and an overall weakening over the past 150 years (GCRP 2018a citing Caesar et al. 2018, Thornalley et al. 2018)

IPCC reports it is *very likely* that the AMOC will weaken over the 21st century; further, it reports it is *likely* that there will be some decline in the AMOC by about 2050, but the AMOC could increase in some decades because of large natural internal variability (IPCC 2013b). IPCC also reports that it is *very unlikely* that the AMOC will undergo an abrupt transition or collapse in the 21st century (for the scenarios considered), and there is *low confidence* in assessing the evolution of the AMOC beyond the 21st century because of the limited number of analyses and equivocal results (IPCC 2013b). However, IPCC (2013b) concludes that a collapse beyond the 21st century for large sustained warming cannot be excluded.

Greenland and West Antarctic Ice Sheets

The sustained mass loss by ice sheets would cause a significant increase in sea level, and some part of the mass loss might be irreversible (IPCC 2013b). For example, under 2°C (3.6°F), about one-third of the Antarctic ice sheet and three-fifths of the Greenland ice sheet would be lost (GCRP 2018a citing Clark et al. 2016). Similarly, there is *high confidence* that sustained warming greater than some threshold would lead to the near-complete loss of the Greenland ice sheet over a millennium or more, causing a global mean sea-level rise of up to 7 meters (29 feet). Current estimates indicate that the threshold is more than about 1°C (1.8°F) (*low confidence*) but less than about 4°C (7.2°F) (*medium confidence*) global mean warming with respect to preindustrial levels. The temperature range of 1.5-2°C (2.7-3.6°F) presents a moderate risk of triggering marine ice sheet instability in Antarctica or irreversible loss of the Greenland ice sheet (IPCC 2018).

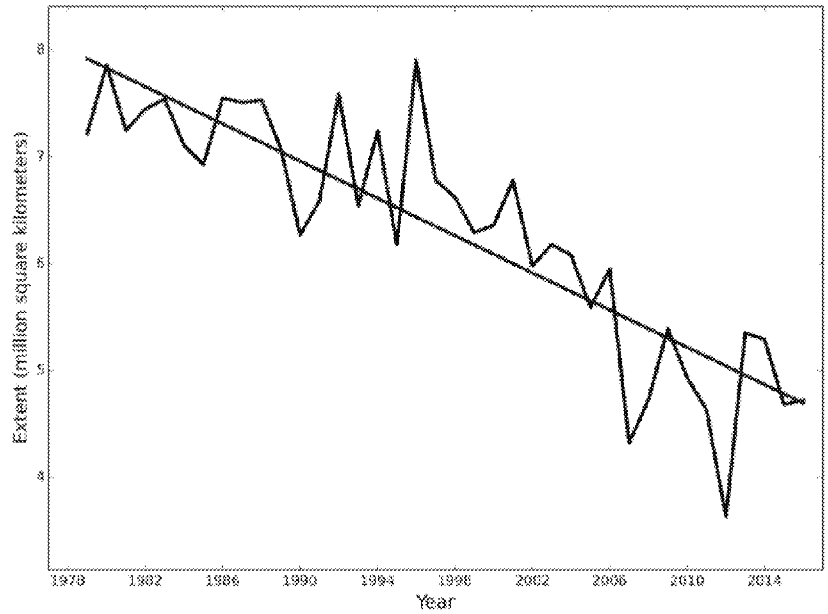
Of particular concern is the potential for abrupt increases in sea-level rise from rapid destabilization and ice loss from glaciers and ice streams grounded on bedrock below sea level. For these glaciers, warming oceans melt and erode the base and cause the ice to float, accelerating losses. In Greenland, most areas of deep water contact between ice sheets and the ocean are limited to narrow troughs and fjord systems that constrict rapid flow into ocean basins, making the likelihood of rapid destabilization during this century low (NRC 2013b).

Abrupt and irreversible ice loss from a potential instability of marine-based (as opposed to land-based) sectors of the Antarctic ice sheet (i.e., ice shelves) in response to climate change is possible, but current evidence and understanding is insufficient to make a quantitative assessment (IPCC 2013b; NRC 2013b; Hansen et al. 2013). That said, two studies (Joughin et al. 2014; Rignot et al. 2014) published since the IPCC (2013a) assessment report indicate that West Antarctic ice shelves have been accelerating their melt in recent decades, that this increase is projected to continue, and that there is little in the regional geography to stop them from an eventual full decline (i.e., an irreversible collapse) as they retreat into deeper water. A recent study by Mengel and Levermann (2014) demonstrates the potential irreversibility of marine-based ice sheet loss and the presence of thresholds beyond which ice loss becomes self-sustaining.

Arctic Sea Ice

Since satellite observations of Arctic sea ice began in 1978, a significant decline in the extent of summer sea ice has been observed, with the record minimum extent—a decrease of more than 40 percent in September, i.e., the month when the minimum in the sea-ice extent typically occurs—recorded in 2012 (Figure 8.6.5-2) (GCRP 2017). IPCC (2013b) suggests that anthropogenic influences have *very likely* contributed to these Arctic sea-ice losses since 1979, and that it is *very likely* that the Arctic sea-ice cover will continue to shrink and thin.

Figure [STYLEREF 3 \s]-[SEQ Figure * ARABIC \s 3]. Average Monthly Arctic Sea-Ice Extent (September 1979–2016)[a]



Source: NSIDC 2016
[a] Ice extent for each September plotted as a time series based on the 1979 to 2016 data. The black line connects the ice extent data points and the trend line is plotted with a blue line.

Rising temperatures are reducing ice volume and surface extent on land, lakes, and sea, with this loss of ice expected to continue. The Arctic Ocean is expected to become essentially ice free in summer before mid-century under future scenarios that assume continued growth in global emissions, although sea ice would still form in winter (GCRP 2017 citing IPCC 2013a and Snape and Forster 2014; NRC 2013b). Based on an assessment of the subset of models that most closely reproduce the climatological mean state and 1979 to 2012 trend of the Arctic sea-ice extent, a nearly ice-free Arctic Ocean in September before mid-century is *likely* for the higher (RCP8.5) scenario (*medium confidence*). A projection of when the Arctic might become nearly ice-free in September in the 21st century cannot be made with confidence for the other scenarios (IPCC 2013b).

Sea ice loss contributes to positive feedback by changing the albedo of the Arctic's surface, affecting formation of ice the next winter (GCRP 2018a citing Abe et al. 2016, Pedersen et al. 2016, and Post et al. 2013). Larger areas of open water in the Arctic during the summer will affect the Arctic climate, ecosystems, and human activities in the Northern Hemisphere; these impacts on the Arctic could potentially be large and irreversible. Less summer ice could disrupt the marine food cycle, alter the habitat of certain marine mammals, and exacerbate coastline erosion. For instance, sea ice is the primary habitat for polar bears. Polar bear movements are closely tied to the seasonal dynamics of sea-ice extent, and the loss of sea-ice habitat due to climate change is a primary threat to polar bears (USFWS 2016). Reductions in summer sea ice will also increase the navigability of Arctic waters, opening up opportunities for shipping and economic activities, but also creating new political and legal challenges among circumpolar nations (NRC 2013b).

Irreversibility of Anthropogenic Climate Change Resulting from Carbon Dioxide Emissions

A large fraction of anthropogenic climate change resulting from CO_2 emissions (e.g., global mean temperature increase, and a decrease in ocean pH) is irreversible on a multi-century to millennial time scale, except in the case of a large net removal of CO_2 from the atmosphere over a sustained period (IPCC 2013b). Surface temperatures will remain approximately constant at elevated levels for many centuries after a complete cessation of net anthropogenic CO_2 emissions. Because of the long time scales of heat transfer from the ocean surface to depth, ocean warming will continue for centuries (IPCC 2013a). A recent study indicates that the Earth may be approaching an approximate 2°C threshold after which the system as a whole would be locked into a rapid pathway toward much hotter conditions that would be accelerated by self-reinforcing feedbacks (Steffen et al. 2018).

Delaying Mitigation

Several studies have shown that delaying mitigation of GHG emissions results in a greater accumulation of CO_2 in the atmosphere, thereby increasing the risk of crossing tipping points and triggering abrupt changes (Anderson and Bows 2011; Friedlingstein et al. 2011; UNEP 2020; van Vuuren et al. 2011a, 2011b; Ranger et al. 2012).

Increases in the Risk of Extinction for Marine and Terrestrial Species

The rate of climate change is increasing the risk of extinction for a number of marine and terrestrial species (NRC 2013b). Climate change can cause abrupt and irreversible extinctions through four known mechanisms (NRC 2013b):

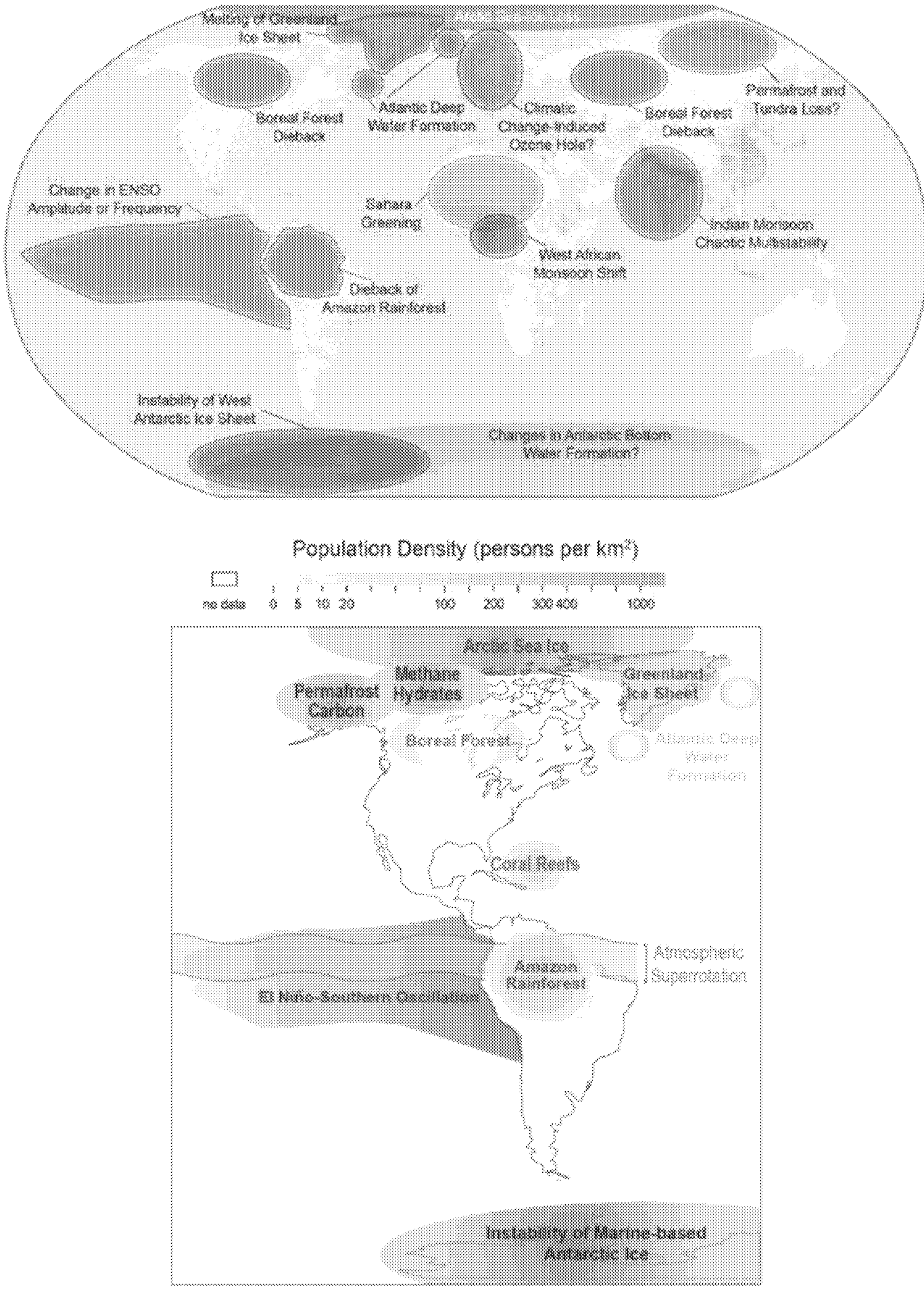
- Direct impacts from an abrupt event, such as flooding of an ecosystem through a combination of storm surge and sea-level rise.
- Incremental climatic changes that exceed a threshold beyond which a species enters decline, for example, pikas and ocean coral populations are close to physiological thermal limits.
- Adding stress to species in addition to nonclimatic pressures such as habitat fragmentation, overharvesting, and eutrophication.
- Biotic interactions, such as increases in disease or pests, loss of partner species that support a different species, or disruptions in food webs after the decline of a keystone species.

It is expected that some species will become extinct or fall below viable numbers in the next few decades (NRC 2013b). IPCC states that there is *high confidence* that a large fraction of species faces increased extinction risk due to climate change during the 21st century and beyond (IPCC 2014b).

Additional Tipping Points

GCRP (2017) and NRC (2013b) indicate a number of other potential tipping points (Figure 8.6.5-3), which are described in this section.

Figure [STYLEREF 3 \s]-[SEQ Figure * ARABIC \s 3]. Potential Tipping Points



Source: GCRP 2017 adapted from Lenton et al. 2008
km² = square kilometer

- **El-Niño-Southern Oscillation (ENSO).** It is *likely* that regional rainfall variability due to ENSO will increase over the 21st century; however, confidence in the amplitude and spatial pattern of ENSO remains low (IPCC 2013b). In the United States, the rainfall variability associated with ENSO events will *likely* move eastward in the future (IPCC 2013a). Research indicates that the frequency of extreme El Niño events increases linearly with global mean temperature; under 1.5°C of temperature warming, the number of extreme El Niño events could double (IPCC 2018 citing Wang et al. 2017).
- **Amazon rainforest.** Deforestation, reductions in precipitation, a longer dry season, and increased summer temperature could contribute to accelerated forest dieback. Important additional stressors also include forest fires and human activity (such as land clearing) (Lenton et al. 2008). In general, studies agree that future climate change increases the risk of the tropical Amazon forest being replaced by seasonal forest or savannah (IPCC 2013a citing Huntingford et al. 2008, Jones et al. 2009, and Malhi et al. 2009).
- **Boreal forest.** The dieback of boreal forest could result from a combination of increased heat stress and water stress, leading to decreased reproduction rates, increased disease vulnerability, and subsequent fire. Although highly uncertain, studies suggest a global warming of 3°C (5.4°F) could be the threshold for loss of the boreal forest (Lenton et al. 2008). Models indicate that under a high emissions scenario (RCP8.5), even without water stress, additional heat could transition the boreal forests into a net CO_2 source (Helbig et al. 2017).
- **Release of methane hydrates and permafrost and tundra loss.** A catastrophic release of CH_4 to the atmosphere from clathrate hydrates[33] in the seabed and permafrost, and from northern high-latitude and tropical wetlands, has been identified as a potential cause of abrupt climate change (GCRP 2017). The size of the CH_4 hydrate reservoir in the arctic is estimated to be between 500 and 3,000 gigatons of carbon potentially being equivalent to 82,000 gigatons CO_2 (assuming the hydrates are released in that state) (GCRP 2017). However, uncertainty exists in the sensitivity of these carbon reservoirs—as measured by the rate of carbon release from stored hydrates per unit of warming—to a changing climate (Mestdagh et al. 2017). These reserves will probably not reach the atmosphere in sufficient quantity to affect climate significantly over the next century (GCRP 2017). Permafrost stores hold an additional estimated 1,300 to 1,600 gigatons of carbon, about 5 to 15 percent of which is vulnerable to being released in the coming century (GCRP 2017 citing Schuur et al. 2015). It is very likely that emissions from thawing permafrost are amplifying carbon emissions and will continue to do so (GCRP 2018a citing Schaefer et al. 2014, Koven et al. 2015, and Schuur et al. 2015; Yumashev et al. 2019). Past research warns that these tundra sources could cause an abrupt release of carbon, causing dramatic warming in the atmosphere (Hansen et al. 2013; NRC 2013b), but more recent literature suggests that the most probable process is a gradual and prolonged release of carbon (Schuur et al. 2015; Mestdagh et al. 2017). These estimates of a slow emissions rate from permafrost and hydrates may be incorrect if anthropogenic GHG emissions cause the Earth to warm at a faster rate than anticipated (GCRP 2017).

To the extent that the Proposed Action and alternatives would increase the rate of CO_2 emissions relative to the No Action Alternative, they could contribute to the marginal increase or acceleration of reaching these tipping-point thresholds. Moreover, while this rulemaking alone would not cause CO_2

[33] Clathrate hydrates are *inclusion compounds* in which a hydrogen-bonded water framework—the host lattice—traps guest molecules (typically gases) within ice cages. Naturally occurring gas hydrate on Earth is primarily methane hydrate and forms under high pressure–low temperature conditions in the presence of sufficient methane (GCRP 2014 citing Brook et al. 2008).

emissions to reach the tipping-point thresholds, it would be one of many global actions that, together, could contribute to abrupt and severe climate change.

8.6.5.3 Regional Impacts of Climate Change

In response to the MY 2017–2025 CAFE Standards Draft EIS, NHTSA received a public comment on Section 9.3.2.1 noting that, "with regard to climate change, regional impacts are likely to be particularly relevant to the public." The comment further encouraged NHTSA to include regional models and information contained in state or regional assessments for each region of the U.S. to illustrate how changes in transportation-related GHG emissions can influence regional climate impacts. In addressing the health, societal, and environmental impacts of climate change in the MY 2017–2025 CAFE Standards Final EIS (NHTSA 2012) and in the Phase 2 Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles Final EIS (NHTSA 2016a), NHTSA included a qualitative assessment of the regional impacts of climate change.

NHTSA recognizes the public's interest in understanding the potential regional impacts of climate change; these impacts are discussed at length in panel-reviewed synthesis and assessment reports from IPCC (at the continent scale), and GCRP (at the U.S. regional scale). In addition to including this material in NHTSA's prior EISs, the Fourth National Climate Assessments (GCRP 2017, 2018a) provide this very regional analysis, reporting observations and projections for climatic factors (GCRP 2017), and the regional and sectoral impacts of climate change (Section 8.6.5.2, *Sectoral Impacts of Climate Change*) for each region of the United States (GCRP 2014). The regions addressed in the Fourth National Climate Assessment (GCRP 2018a) include the Northeast, Southeast, U.S. Caribbean, Midwest, Northern Great Plains, Southern Great Plains, Northwest, Southwest, Alaska, and Hawaii and U.S. Affiliated Pacific Islands. Additionally, individual states, such as California, have completed in-depth local climate change assessments (Bedsworth et al. 2018).

In the NEPA context, there are limits to the utility of drawing from assessments to characterize the regional climate impacts of the Proposed Action and alternatives. The existing assessment reports do not have the resolution necessary to illustrate the effects of this action, because they typically assess climate change impacts associated with emissions scenarios that have much larger differences in emissions—generally between one and two orders of magnitude greater than the difference between the No Action Alternative in 2100 and the emissions increases associated with all the action alternatives in 2100. The differences between the climate change impacts of the Proposed Action and alternatives are far too small to address quantitatively in terms of their impacts on the specific resources of each region. Attempting to do so may introduce uncertainties at the same magnitude or more than the projected change itself (i.e., the projected change in regional impacts would be within the noise of the model). Agencies' responsibilities under NEPA involve presenting impacts information that would be useful, relevant to the decision, and meaningful to decision-makers and the public.

For a qualitative review of the projected impacts of climate change on regions of the United States, readers may consult Section 5.5.2 of the MY 2017–2025 CAFE Standards Final EIS (NHTSA 2012), Section 5.5.2 of the Phase 2 Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles Final EIS (NHTSA 2016a), and the Third and Fourth National Climate Assessments (GCRP 2014, 2017, 2018a). These assessments demonstrate that the impacts of climate change vary at the regional and local level, including in strength, directionality (particularly for precipitation), and particularity. These variations reflect the unique environments of each region, the differing properties of the sectors and resources across regions, the complexity of climatic forces, and the varied degrees of human adaptation across the

United States. However, the overall trends and impacts across the United States for each climate parameter and resource area are consistent with the trends and impacts described in Section 8.6.5.2, *Sectoral Impacts of Climate Change.* Because the Proposed Action and alternatives are projected to result in only very minor increases in global CO_2 concentrations and associated impacts, including changes in temperature, precipitation, sea level, and ocean pH, as compared to the No Action Alternative, the climate impacts projected in those reports would be expected to increase only to a marginal degree.